

STUDY AND DEVELOPMENT OF
NONDESTRUCTIVE WELD
INSPECTION TECHNIQUES

Phase I

Final Report

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SECTION 1

INTRODUCTION

This is the final report covering the first phase of a program whose objective is the Development of Nondestructive Weld Inspection Techniques (NDT)*. Work by Walter V. Sterling, Inc. (WVS) on this program was initiated under NASA/ARC contract NAS2-4166 on February 27, 1967 for the purpose of developing nondestructive test techniques and the associated instrumentation for use in microcircuit welding.

Our work during this initial phase has been devoted to three major tasks. The first of these was a study of the existing literature relating to micro-welding operation and evaluation techniques, augmented by visits to aerospace organizations interested in and using wirewelding for electronic assembly.

*For simplicity, NDT is used in the remainder of the report to mean Non Destructive Testing.

The second task was concerned with the selection of weld attributes for NDT instrumentation, and the development of the applicable instrumentation. The third task area covered all aspects of evaluating the effectiveness of the NDT techniques that were developed.

In this report, the complete work of Phase I is discussed in summary form in Section 2, and provides a detailed evaluation of the conclusions reached regarding the effectiveness of the NDT techniques being used. Section 3 of the report presents a detailed discussion of the complete program. Included as appendices to the report are an NDT-related bibliography and a list of organizations and persons contacted initially in the program.

The perception by NASA of the need for the development of an effective microwelding NDT system to aid in the consistent production of good weld joints has been further substantiated by the organizations visited. Those who were actually manufacturing hardware found it necessary to maintain constant vigilance over a somewhat diverse group of product and process attributes which they believed would control product quality. The factors being used for control varied significantly between organizations but among them were the following common features:

- . MATERIALS IDENTIFICATION AND SPECIFICATION CONTROL is essential to component manufacturers' lead materials, plating thicknesses, surface contamination, cleaning, and differences in weldability of different lots of ostensibly the same wire material.

- . EQUIPMENT STANDARDIZATION in a production facility is essential where different welding stations are to be used interchangeably. This is not assured simply by procuring and installing quantities of similar equipment models from the same equipment vendor but must be accomplished by consistent machine certification, calibration, and maintenance.
- . EQUIPMENT CALIBRATION AND MAINTENANCE is required on a periodic basis to maintain repeatability of welder performance. This must include measurements of the welder electrical output characteristics and testing of the welding heads for welding force and follow-up performance.
- . PRODUCTION OPERATION of the welding stations requires procedures to insure use of the correct weld schedules, frequent attention to electrode surface dressing, and periodic pull tests on sample welds to verify total process control.
- . OPERATOR TRAINING AND QUALIFICATION require unique attention in that operator errors are ranked high among the causes for producing bad welds. In addition to the need for operator training covering the fundamentals of good welding practices, special qualifications for application to particular welding machine and module configurations has been found important to the production of good welds.

- . VISUAL INSPECTION of welds is universally accepted as the primary quality assurance method. To be effective, pictures and diagrams of acceptable, as well as unacceptable, welds must be used to provide a comparative basis for acceptance. Many organizations provide inspection training for the production line welding operators to maintain high quality. Use is often made of weld joint appearance characteristics derived during the development of the weld schedules.
- . CONTINUING MANAGEMENT ATTENTION is essential to maintain a successful production welding operation. Buying standard welding equipment and hiring capable operating personnel are only two of the several areas requiring management action. Examples of the span of required management attention are:

Assuring that a system is established and followed for producing engineering designs of consistent and producible nature for the welded modules.

Provision for determining that these module engineering designs are consistent with the capabilities of the welding production facilities to be used.

Determination that adequate supervision, equipping, and training of production personnel are continued in the areas outlined in the preceding paragraphs.

The objectives of Phase I NDT investigations have been successfully demonstrated. The laboratory studies have been carried out under closely controlled welding conditions with

common welding practice errors purposely introduced to produce faulty welds. The second phase, which is now in progress, is designed to prove the effectiveness of the NDT system in actual production line operations. We will develop from the Phase I NDT laboratory equipment, a prototype operation of two prototype models, and generate an evaluation test plan for application of these prototype units on aerospace welded module production lines.

This will be accomplished in two steps: first, prototype models of the NDT weld evaluator will be built for production line use, certified in our laboratories, and a production evaluation plan developed. Then, as the second step, these equipments will be installed on the manufacturing lines of two major aerospace companies for objective evaluation in production situations.

SECTION 2

SUMMARY AND CONCLUSIONS

A comprehensive study of the field of wire welding technology, as it applies to electronic circuit fabrication, has been made in order to devise a means for determining weld quality in a non-destructive manner. This study has been supported by concurrent laboratory investigations of the instrumentation techniques showing the greatest promise of providing useful nondestructive measurements.

Three techniques were selected and used in combination to form an NDT "system" with the ability to provide consistent and valid indications of weld quality. This system was then subjected to a varied and extensive evaluation program in our laboratories by intentionally fabricating faulty welds whose defects represented a cross-section of the most probable failures resulting from machine,

operator, and material deficiencies. Our conclusions from this combined analytical, experimental, and critical evaluation program are the following:

THE ABILITY TO MAKE NONDESTRUCTIVE MEASUREMENTS
OF IMPLICIT WELD QUALITY HAS BEEN CLEARLY PROVED

Bad welds have been intentionally fabricated in numerically meaningful quantities, representing their normal types of occurrence in tens of thousands of production welds. These, together with good welds also produced under controlled conditions, have been judged "good" or "bad" by the NDT instrumentation developed on this program and then pull tested to determine their quality in terms of torsional shear strength. The NDT measurements have shown excellent correlation with the established strengths for good and bad welds.

THE MEASUREMENTS PROVIDE VALUABLE INDICATIONS OF
PROCESS DRIFTS BEFORE DEFECTIVE WELDS OCCUR

A secondary result of significant value is the sensitivity of the measured attributes to deviations in welding conditions which, if continued, will result in bad welds. Properly used, this can supply process control information that will prevent the occurrence of poor quality welds.

MEASUREMENTS OF THREE DIFFERENT ATTRIBUTES ARE
REQUIRED TO PROVIDE THE MOST PRACTICAL SYSTEM
CONSIDERING BOTH PRODUCTION HARDWARE GEOMETRY
AND INSTRUMENTATION DIFFICULTY

Based upon consideration of actual geometry of welded circuits and welded modules, and the practical problems of instrumentation, the measurement of voltage pulse, infrared radiation, and setdown were selected for detailed laboratory investigations. These were studied singly and in combination, and the use of "two-out-of-three" logic was found superior to the indications of any individual attribute.

The initial work on this project included what we believe was a thoroughly comprehensive study of the applicable literature plus the actual practices and techniques currently used by industry. Over 120 articles related to nondestructive weld testing were carefully reviewed and visits were made to the laboratories and/or production lines of over 20 industrial and government organizations. The information gathered from these sources, together with our own experience in the welding research field, provided the basis for selecting the most promising approaches to nondestructive measurement or testing. The

following six techniques were selected for detailed consideration; the last three were chosen for hardware implementation:

- . Eddy current measurement
- . Weld joint resistance measurement
- . Sonic and ultrasonic measurement
- . Weld voltage pulse monitoring
- . Infrared radiation measurement
- . Setdown measurement

GENERALLY ACCEPTABLE DEFINITIONS OF WELD QUALITY
DO NOT EXIST

Our survey of industry and government activities in wirewelding disclosed that a widely varied group of visual or "cosmetic" acceptance criteria are being used to implicitly judge pull strength and metallurgical features. Our basic premise in this regard was that in order to be "good", a weld must satisfy two practical conditions; namely, it must have adequate electrical conductivity and adequate physical strength, with the definition of "adequate" being the major problem. Measurements of weld conductivity performed by WVS and other organizations, in the course of investigating the NDT utility of such measurements, revealed that weldment resistance was negligible when compared to circuit, component and lead

resistance, and lacked correlation with pull strength. Therefore, for the purpose of our studies, a minimum weld strength limit for a specified sample size and material combination has been used since electrical conductivity will always be adequate if the weld will hold together physically. (We recognize that there may be exceptions to this in semiconductor or oxide bonds but they have not occurred in our studies.)

SECTION 3

DETAILED DISCUSSION

A. BACKGROUND STUDY

The starting point for this development program was a thorough study of all available background data regarding nondestructive weld testing. This was coupled with a series of visits to major aerospace and government organizations currently involved with micro-circuit welding technology, to insure that the most up-to-date developments would be used as the point of departure for our work*.

Based upon the literature research, our previous welding research studies, and conferences with other organizations knowledgeable in this field, the following techniques were considered for more detailed investigation.

*The results of these visits were reported in detail in our Monthly Status Report No. 2, WVS Rpt. No. 67-5-35 and a list of contacts made is presented in Appendix B.

- . Eddy current measurement
- . Weld joint resistance measurement
- . Sonic and ultrasonic vibration
- . Weld pulse monitoring
- . Infrared radiation measurement
- . Setdown measurement

Our findings regarding each of these techniques were as follows:

1. Eddy Current Testing

Eddy current testing has been widely and effectively employed for NDT of electrically conducting materials. In principle, detection of some of the factors directly relevant to weld joint quality evaluation is possible using eddy current techniques. This would include voids, cracks, and some attributes of metallurgical structure. However, eddy current magnitudes induced in the test specimens are directly responsive to size and geometry of the material, and position of the test coil with respect to the material. Thus, the complexity of the many possible weld joint forms and control of their orientation with respect to the test coil or probe appeared to present too great an obstacle to effective application within the time scale of this investigation.

2. Weld Joint Resistance Testing

The concept of weld joint resistance testing is based on the postulate that post-weld joint resistance should bear a strong relationship to weld joint area; and that weld joint area is, in turn, a prime determinant of weld pull strength. However, a number of investigations (including work in our own labora-

tory) have tried this approach using a variety of methods with the general conclusion that there is no useful correlation between post-weld joint resistance and weld pull strength.

3. Sonic and Ultrasonic Vibration

The idea that a weld joint may actually be undergoing physical stress and strain while testing with sonic or ultrasonic vibrations, gives this method a unique logical appeal. It appeared that an appropriate vibration energy excitation method coupled with measurement of the resulting stress-strain-rate behavior, could reflect the effects of such weld joint attributes as work hardening and bonded area. This, in turn, could be expected to permit direct, effective weld-by-weld correlation with pull strength, which also is influenced directly by these kinds of physical characteristics. While this approach appears to have merit, most of the applications have been in the area of large structural type welds, with much less complex structural interactions than the typical electronic module. It was therefore not selected as a primary approach for this project.

4. Pulse Monitoring, Infrared Radiation, Setdown

The remaining three techniques, weld pulse voltage monitoring, infrared radiation, and setdown, were ultimately selected by WVS for instrumentation, and as a consequence, these techniques are not further discussed here, since they are examined in detail in later sections.

B. SELECTION OF WELD ATTRIBUTES FOR INSTRUMENTATION

The attributes currently being used by industry for differentiating "good" welds from "bad" welds, after the production weld is made, are primarily cosmetic — or visual — and subject to a wide variance in personal interpretation. In addition, those attributes of a finished weld that may be amenable to measurement (such as eddy current loss, thermal conductivity or acoustic transmissibility) pose very difficult instrumentation problems because of the highly variable circuit geometry. As a consequence, while they are considered an attractive basis for the subsequent development of a post-weld inspection method, they did not appear immediately feasible for investigation within the scope and schedule of the present NDT program.

It was therefore determined that weld testing, in-process, was potentially more immediately realizable on a practicable basis, than weld testing after-the-fact since it was evident that measurements could readily be made of the following dynamic parameters occurring while the weld is being made.

WELD PULSE VOLTAGE

One of the factors relating to weld quality is the variation in resistance through the weld joint while the weld is being made. Analysis of the welding electrical circuit revealed that two impedance factors are of concern: the dynamic resistance of the welds and the impedance of the total welder circuit, which is fixed. The welding

current produces a voltage drop across the weld that is a function of weld resistance. The nature of this voltage pulse appearing across the welding electrodes during the welding cycle could thus be indicative of weld quality.

INFRARED RADIATION

Another welding process attribute that appeared amenable to instrumentation was the thermal energy of the weld. The application of force, generation of sufficient thermal energy at the weld faying surface, and maintenance of proper heat energy distribution across the weld joint are key factors in making a resistance weld. The short duration high temperatures that are an essential part of the welding process produce a considerable yield of infrared radiation. The presence of infrared radiation in correct quantities or with the proper transient "signature" appeared to provide a ready means for indirectly measuring the thermal energy generated during formation of a weld, which, in turn, should relate to the weld strength and other acceptance criteria.

DYNAMIC
SETDOWN

A third weld attribute which is known to have a measure of correlation with weld quality* is the change in total thickness of the two materials from pre-weld to post-weld condition. This change, referred to as setdown, has been recognized in welding process control documentation, quality control requirements, and specifications, as a welding attribute requiring controlled limits. In actual practice, the setdown limits are usually employed as guides for visual inspection in production welding rather than being determined from actual gage measurements. However, earlier WVS investigations verified the existence of higher level of correlation between the dynamic setdown occurring during the weld and weld quality, and also verified the practicality of its in-process measurement.

The rationale for the selection of welding pulse waveform, infrared radiation, and dynamic setdown for further study and instrumentation can thus be summed up as follows:

- . Laboratory investigations by WVS and others have shown usable correlation between the individual attribute parameters and subsequent weld quality.

*See WVS Rpt. No. 67-7-2, Quarterly Report No. 1

- . All three attributes can provide dynamic in-process data.
- . Simultaneous instrumentation of all three attributes is practical and has promise of greater weld quality revelation than has been shown by the parameters taken singly.

C. WELD ACCEPTANCE CRITERIA

In order to make the investigation of a practical approach to NDT meaningful, the criteria for "good" and "bad" welds must be adequately defined. The analytical and more subjective techniques currently employed by industry are partly for process control and partially to establish whether the welded connections will perform satisfactorily under the required environmental conditions. When considering this latter criterion for acceptability, at least two conditions must be met in order to assure a practically usable weld:

- . Adequate electrical conductivity
- . Adequate physical strength

The definition of "adequate appeared to be the first problem for each of these attributes; and with this in mind, the following discussion of acceptance criteria is presented.

1. Current Aerospace Acceptance Criteria

The acceptance criteria for a weld are generally not the same for any two manufacturers, even though the operations may be very similar, and it is certain that some requirements will accept bad welds while others will reject good ones. In an attempt to resolve the question, a representative sampling of military and other user specifications was analyzed and the results are discussed on the following pages.

Bearing in mind that the minimum criterion for a "good" weld is that it will not break in its exposure to all use environments, no visual or physical requirement is useful unless it correlates with weld strength; further, weld strength aver-
ages are not valid for this purpose unless they also insure positive control of minimum strength for every weld made.

Our review of the various requirements in ten specifications from cognizant organizations is presented in detail in Table 1 and shows the following:

- . Six of these specifications do not use strength criteria in developing a weld schedule; of the four that do, the minimum required for average strength, \bar{x} , ranges from 30% to 60% of the weaker wire. The sample sizes for setting the weld schedule range from 3 to 250. Five of the specifications do not specify the sample size.
- . Weld schedule proofing is required by eight. This consists of an extensive confirmation of the selected weld parameters. Four specifications have a fixed minimum weld strength. No two specifications use even similar criteria for the range of allowable weld strength variability.
- . Visual criteria are highly subjective and thus difficult to apply because of personal interpretation factors. Characteristics specified for examination range from 3 to 11; three organizations require sampling only, five require

Source	WELD SCHEDULE										PRODUCTION CONTROL									
	Development			Proofing				Production Verification			Strength Control				Deformation			Visual		
	\bar{x}	x_{min}	n	x_{min}	x_{var}	n	Alternate	Req'd?	n	Prod. Sampling	Basis	n	Where	Freq. Hrs.	D	d_1	d_2	No of Items	Freq. of Insp.	Magnif.
A	--	--	-	--	-	-	---	No	-	0	--	--	-	-	<35	<50	<50	11	100%	30X
B	>.6y	Det.	Any	6#	$\bar{x} \pm 15\%$	Any	>.5y	Yes	46	100%	\bar{x}, R	>5	Each Head	5	-	<60	<60	5	100%	10-15X
C	Det.	--	10	Det.	Det.	50	---	No	-	0	$>x_{min}$	3	-	4-6	<35	-	<50	8	-	10-30X
D	Det.	--	>3	3#	Det.	-	---	No	-	Sample	Weld Sched.	4	Each Machine	4	-	-	<50	7	-	<20X
E	>.5y	--	-	--	C_1	45	$C_2 \text{ \& } C_3$	No	-	0	Weld Sched.	3	-	4	<35	-	<50	7	100%	>10X
F	Det.	Det.	5	--	-	-	---	Yes	41	0	\bar{x}, R	4	Each Mach-Op	4	<35	-	<50	7	100%	10-15X
G	Det.	--	20	$Q \geq .5$	\bar{c}	20	---	Yes	40	0	x_5	5	Each Mach-Op	4	5-75	-	<50	7	100%	10-15X
H	Det.	Det.	-	5#	-	A	---	Yes	30	0	x_{min}	4	Each Head	>4	-	-	-	3	Sample	--
I	>.5y	Det.	-	5#	-	A	Lowest of 5# or .5y	Yes	30	0	x_{min}	4	Each Head	8	-	-	-	5	Sample	--
J	>.3y	5#	250	5#	x_{min}	770	A	Yes	360	0	\bar{x}, R x_{min}	5	Each Mach-Op	4	-	-	-	8	Sample	10-20X

EXPLANATORY NOTES

\bar{x} = average weld strength	x_{min} = lowest weld strength in sample - sensitive to sample size
n = sample size	D = total weld cross section deformation in % - setdown
x_{var} = weld strength variability	d_1 = deformation of smallest wire into largest %
$x_5 = \bar{x} \pm 3 (\bar{r} + .25)$	d_2 = deformation of either wire, whichever is greatest, in %
$Q = \frac{\bar{x} - 5\bar{r}}{y} (100)$	Det. = to be determined during schedule development
x_{max} = maximum weld strength	\bar{c} = standard deviation, $\sqrt{\frac{\sum (x - \bar{x})^2}{n}}$
$C_1 = .20$	C = coefficient of variability $\frac{x_{max} - x_{min}}{\bar{x}}$
$C_2 = .25 \text{ for } 90\%; .35 \text{ for remainder of weld samples}$	Y = average breaking load of weakest wire
$C_3 = .35 \text{ for } 90\%; .45 \text{ for remainder of weld samples}$	A = compute from Application Reliability Requirements
R = range of observed values	

Table 1
SPECIFIED WELD ACCEPTANCE CRITERIA
(TEN SOURCES)

100% examination of all characteristics, and seven specify optical magnification which ranges from 10 to 30.

- . Production control requirements vary widely and include verification of the weld schedule on production machines, in-process controls and visual criteria. Six require verification with sample sizes ranging from 30 to 360. In-process sampling is required by nine, and sample sizes range from 3 to 5; the sampling period ranges from 4 to 8 hours; the sampling differs — some require only that welds be made at the weld head, others specify that each machine-operator combination be identified. The control criteria differ among organizations and are distributed as follows:

$R(\text{two})^*; \bar{x}, R, x_{\min}(\text{three}); \bar{x} + 3(\sigma + .25)$

$(\text{one}); C = \frac{x_{\max} - x_{\min}}{\bar{x}} (\text{one})$

Weld schedule, with no other requirement stated (1)

Specification of visual requirements (7)

Requirement for less than 35% total setdown (4)

Allowance of 5 to 75% total setdown (1)

Requirement that no wire shall be more than 50% deformed (6)

Specification that no wire shall be more than 60% deformed (1)

*See Explanatory Notes in Table 1 for definitions of terms.

There are thus no uniform criteria in general use, although setdown of 35% appears to be the most uniformly accepted visual or physical criterion. It is important to know how accurately this or other criteria fit actual situations, and a comparison of these specifications is afforded by using the data derived from actual production welding. To provide such a comparison, extensive data from one source were analyzed. The data were obtained from large samples and included expected production variables of machines, operators and materials, and represented an achievable production line situation for each combination given.

From our analysis of the experimental data on the commonly used weld joint material combinations, it was shown that the average pull strength, \bar{x} , as a fraction of the pull strength of the weaker wire of a pair, ranged from 48% to 89%; setdown ranged from 8% to 35%, σ in % of \bar{x} varied from 5.7% to 18%; x_{\min} in % \bar{x} varied from 50% to 80%. The use of σ as a control for x_{\min} was tested by examining their ratios, σ/x_{\min} , which should be a constant if σ is to be used. The ratio varied from 3.1 to 13 and the use of normal statistics for a measure of x_{\min} , therefore, does not appear valid. If the weld strengths are not normally distributed, estimates of the fraction defective based on the mean and standard deviation will not be the same as if the weld strengths were normally distributed. Differences on this score may become especially serious when we are dealing with very small fractions defective, as is the case with high reliability requirements.

The establishment of criteria for good and bad welds is further complicated by the fact that each material combination behaves differently even when normalized. We conclude from

our analyses that as a limit the schedule should not be accepted unless \bar{x} is greater than 50% of the weaker member of a welded pair. It should be pointed out at the same time, that some combinations will be unacceptable in relation to actual capability if \bar{x} is as low as 50% (e.g., 0.020" x 0.030" "A" nickel bus with \bar{x} = 89%); therefore, variability criteria are required together with a minimum \bar{x} , or a variable \bar{x} may be in order. A physical value of interest is x_{\min} in % of \bar{x} , but determination of this parameter is sensitive to sample size and requires a large sample for production application precision, and comparisons must be made only on equal sample sizes. For sample sizes of about 800, the value of x_{\min} should be slightly less than 50% of \bar{x} (smaller sample sizes will require a smaller percent). The deviation of x_{\min} from \bar{x} will be significantly better for many combinations (e.g., .040" Kovar to 0.021" x 0.030" "A" nickel bus).

The various applications of welded joints further require that certain weld combinations, regardless of quality, be excluded because of applied stresses. For this purpose, an empirically chosen minimum should be applied and combined with the schedule achievements of \bar{x} and variations. Process controls can be performed on a periodic sampling of welds which are pull tested and plotted using \bar{x} , R and x_{\min} limits properly chosen. The schedule for each type of material pair will have to have its own characteristic limits. The correlation of one or more nondestructive tests during each weld has a good chance of positively qualifying the weld. Range limits of strength for each schedule are required to bear a known correlation with range limits of each NDT method and will undoubtedly require different limits for each weld combination. This will be accounted for in the NDT production line evaluation plan. For an ultimate NDT system production configuration, the settings

needed for limit controls can be included with the weld schedule settings by the use of a pre-punched card, or similar method, to prevent errors in setting such control limits.

2. WVS Acceptance Criteria

As a result of the analysis of existing welding specifications, it was apparent that minimum weld strength criteria were currently in general use which could be applied to our NDT study. Accordingly, the following approaches to generation of weld strength criteria were developed:

- . An optimum weld schedule would be developed for each set of weld joint materials selected. The average strength of welds constructed at the selected schedule would be required to be at least 50% of the average strength of the weakest weld material.
- . Sample quantities of welds would be constructed by a competent operator and individual torsion-shear pull strength data obtained. The minimum weld strength required would be not less than 50% of the average strength for the sample.
- . For later production line evaluation of the prototype NDT system, the minimum acceptance requirement for weld-to-weld strength would be derived from detailed analysis of the data resulting from the sample runs, strength data derived from the measurement program, and the ultimate resolution of data derived from the prototype NDT instrumentation. These deviations would utilize concepts of average, minimum, and ranges of values such as defined in Duncan's Quality Control and Industrial Statistics. The purpose of this would be to tie in production line periodic sample weld measurements with the module production NDT requirements.

- . An additional overriding minimum strength limit would be derived for each production line weld application. This limit would be established from expected product environment rather than from weld schedule data. This would protect against using otherwise "good" welds where they are inherently too weak to survive the use environment.

A review of current industry acceptance criteria relative to total weld deformation (setdown) showed that in four of the five cases where a specification existed, 35% was the limit established. In WVS laboratories, the experience with many materials has been that welds with setdown in excess of 35% exhibit poor cosmetic appearance and have a tendency to possess a poor internal characteristic. In welds where setdown exceeded 35%, voids and cracks were common. As a result, a limit of 35% was established for weld acceptance for the development phase covered by this report. This limit is subject to revision for later production application on different materials and on other welding machine configurations.

D. PROCESS CONTROL MONITORING

Adequate production control of the welding process is clearly essential for maintaining a high quality of welded connection output. Current industry practices and production control requirements have been discussed in Section C. Mention was made of the potential value and our intention of employing NDT parameters to supplement current practices during the NDT production line evaluation phase.

While the primary objective of the NDT program is assessment of the quality of each individual weld, a major additional value as a process control is also evident from the data. To demonstrate this in our experimental program, we have induced controlled deviations from optimum welding conditions. The weld pairs have demonstrated tolerance toward many of these deviations by retaining acceptable pull strengths. However, in many of these instances, one or more of the NDT parameters have given data values consistently outside their acceptable limits.

Thus, for process deviations not yet serious enough to reject welds, one or another of the NDT parameter measurements have shown ability to indicate process control deviation. In a production process, these parameters can be watched for trends to indicate progressive degradation of the welding process. This information may then be used to initiate remedial action in time to prevent bad welds which might occur due to any systematic process control deterioration.

The NDT data application to process control has tremendous advantage over the traditional periodic pull test coupon methods of control. This advantage lies in the fact that the NDT data can be made available for process control evaluation at any time during a production run, under actual production operating conditions, and without any interruption to the production. The sensitivity of the system's detection capability spans the range from subtle degradations in the welding machine to poor operator techniques, including detection of missed welds.

Some indications of these process control detection capabilities will be presented in the data analysis section of this report.

E. WELDING EQUIPMENT SELECTION

Our survey of the aerospace industry indicates that a wide variety of cross-wire welding equipment is being used, and that the capacitor discharge power supply is the predominant generic type in use. Within this category of welders, many excellent types are found including Taylor-Winfield, Hughes, Raytheon, Sippican, Unitek and others.

The selection of the specific welder head and electrode configuration to be used in this study was dictated by the considerations outlined in the following paragraphs.

An early decision was that instrumentation directly applicable to a typical welder type and weld geometry — if proven successful — must subsequently be applicable to other welder configurations. In addition, to provide a high degree of welder performance repeatability, certain welder characteristics were recognized by our survey contacts as being advanced and desirable. These characteristics include:

- . Power supply regulation. This minimizes variations in welding pulse energy with power line variation.
- . SCR firing circuit. Use of silicon controlled rectifier circuitry for discharging the welder capacitors into the transformer has been shown to produce greater pulse-to-pulse uniformity than can be obtained by use of a firing relay with its contact resistance variability.

- . Transformer core pre-biasing. The state of magnetization of the welder transformer core (at the instant before the charged capacitor bank is connected to its primary windings) influences significantly the characteristics of the welding pulse. This initial state can vary with the history of the previous weld made on the machine (e.g., different weld schedule, circuit ringing). The biasing circuit passes a reverse current through the transformer between welds, and brings it to a consistent point on its magnetic hysteresis curve. This allows more consistent energy transfer through the transformer.

It was determined that the Unitek (Weldmatic) Model 1-065-03 had all of these desired characteristics. It was also determined that the Unitek Model 1-048-02, already in use in our laboratory, could be readily modified to include all of the capabilities of the Model 1-065-03, and was therefore selected for use on this study.

Details for this welder power supply are:

- . Energy storage ranges: 0.2 to 20 watt-seconds and 0.7 to 100 watt-seconds
- . Discharge time: (at 50 watt-seconds)
normal pulse -- 0.0035 second; long pulse -- 0.0078 second
- . Capacitor Bank: 1610 microfarads (measured)
- . Capacitor Storage Voltage: 20 to 408 volts dc, continuously adjustable
- . Input Voltage: 105 to 130 volts ac
- . Maximum Repetition Rate: 80 welds per minute at 100 watt-seconds

To provide additional control over welding variables, several other features were included in our laboratory weld station.

Provision was made to externally monitor the capacitor bank voltage using a precision voltmeter. This yielded more precise measurement than the 2% voltmeter (equivalent to 4% in watt-seconds) incorporated in the welder. In addition, the flexible cables normally supplied to connect the welder power supply to the welding head were replaced by rigid fixed-geometry copper bus bars. There were two basic reasons for this change. First, it was found in early studies that shifts in relative positions of the cables due to the mutual magnetic field coupling effects from the hundreds of amperes welding current would affect the pulse waveform. Secondly, the large area bus bar connections employed provide better control of welder secondary circuit resistance. Earlier WVS studies had pointed out that significant changes can occur in the welding process as a result of secondary circuit resistance changes.

To provide availability for comparative studies, a second weld station was installed alongside the primary station just described. This station utilizes a Unitek (Weldmatic) 1048B power supply, which contains no SCR firing circuit, no transformer bias circuit, and uses normal cable connections to the welder head. This is typical of many installations in current use.

The Unitek (Weldmatic) Model 2-032-03 welding head was chosen to meet aerospace packaging of discrete components in cordwood packages. This head is designed for connection to the chosen power supply, and has the following specifications:

- . Force: 4 ounces to 15 pounds,
continuously adjustable

- . Throat Depth: 2-1/2 inches
- . Electrode Stroke: 1.2 inches
- . Firing Control: automatic, fires at preset force
- . Force Application: swing foot pedal

The electrode configuration selected for use in the NDT study is representative of types widely employed in the aerospace welding field. The electrode diameters must be small enough for clearances between leads and buses, and this is provided for in two generally available configurations. Both of these have 1/8" diameter cylindrical shanks. One type has a conical taper toward the tip, and the other reduces to a short length of 1/8" diameter cylindrical section at the tip. Tapered electrodes are quite acceptable, but are subject to some variation in surface area as electrode material is removed during tip servicing. Therefore, standard 1/16" diameter cylindrical electrodes (1/8" shanks) were chosen to provide uniform tip area bearing against the weldment.

The electrode-to-electrode included angles, most commonly used by the aerospace welding industry, vary between about 50° to 70°, according to the specific application. The applicability of NDT techniques is not dependent upon the values within this range of inter-electrode included angle. A maximum of 70° was allowed for in the installation of NDT monitoring sensors as it is the largest angle expected to be in use.

As a matter of interest (as shown in Figure 1A), the clearance between the fixed electrode face and the nearest interfering .030" ribbon is .045" minimum for the 50° electrode-to-

electrode angle. A 70° included angle, as shown in Figure 1B, is used and recommended where a higher electrode force than 8 pounds is required. For this 70° case, the ribbon clearance required is .050" minimum. Clearance for the moving electrode must be considered in module design and must include the bus and leadwire between the electrodes, plus clearance to permit electrode positioning.

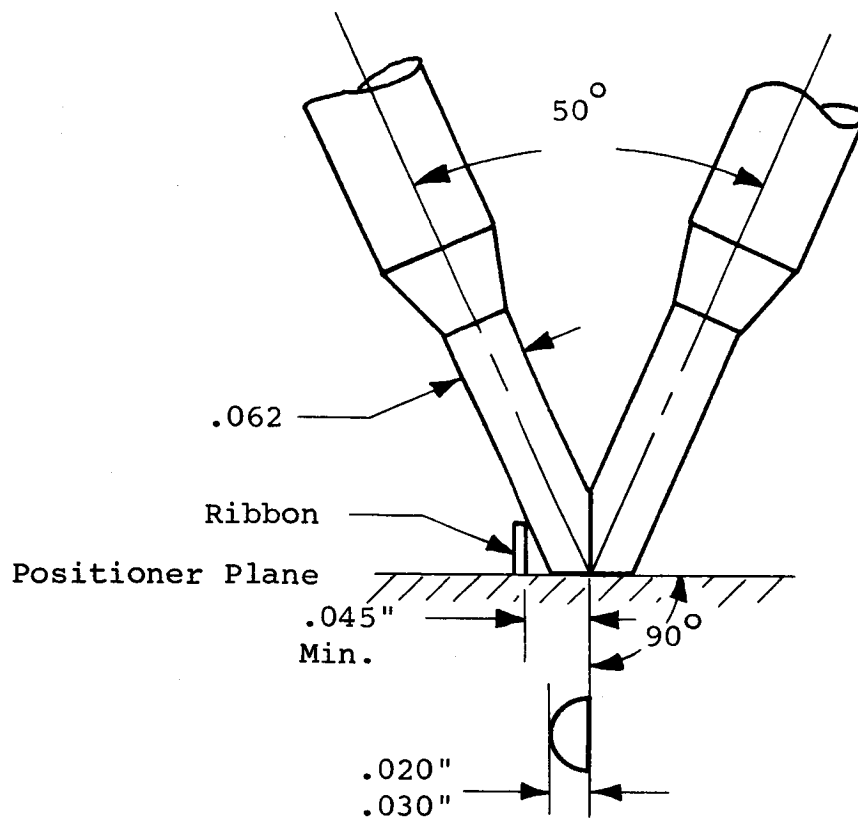


Figure 1A

WELDING ELECTRODE CONFIGURATION 50°

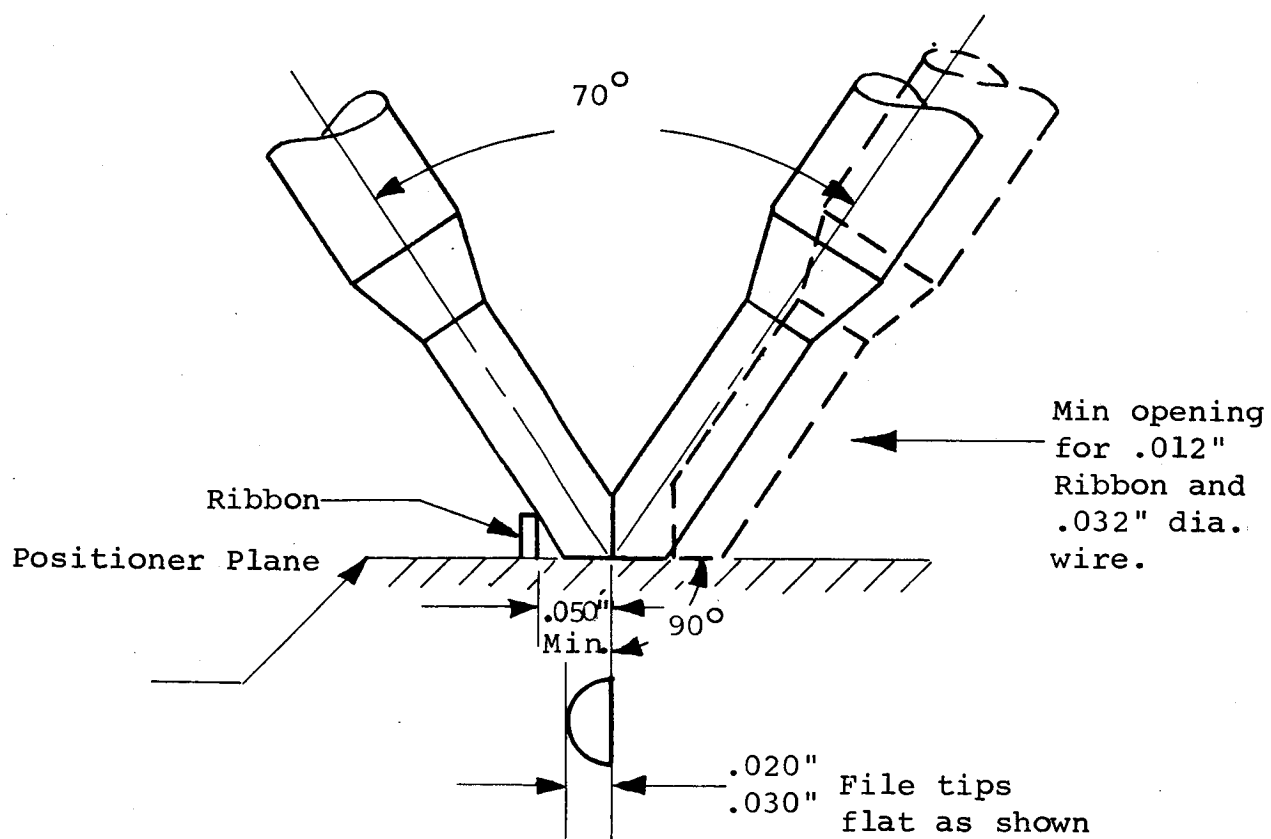


Figure 1B

WELDING ELECTRODE CONFIGURATION 70°

F. WVS WELD STATION CALIBRATION TECHNIQUES

A high degree of operational reliability and repeatability has been built into the weld station equipment employed in our NDT study. However, our investigations into the operation of this complex equipment have shown that welder performance variabilities occur which are critical to our controlled NDT measurements. These performance variabilities are the normal resultants of operating life, as well as maintenance actions, and involve such elements of the system as:

- . Energy storage capacitor bank
- . Regulation and measurement of capacitor charging voltage
- . Resistance of the discharge circuit from capacitors through the transformer primary
- . Welder transformer characteristics
- . Resistance of the conductors and electrical joints in the high current carrying secondary circuit down to and including the weld head electrode faces
- . Inter-electrode force and other characteristics of the welder head affecting follow-up motion

In order to emphasize the essential need for careful weld station control, an example of the kinds of problems detected and remedied in time to prevent degradation of the NDT data is given here in detail. This example involved the failure of the silicon controlled rectifier (SCR) which controls the primary current flow into the welder transformer from the capacitor bank. Before the start of a group of welds, our

customary pre-welding performance verification procedure revealed a significant change in weld pulse output from the normal value for this function. Diagnostic action was taken immediately, resulting in isolation of the cause for the output change to a failing SCR. The welder performance verification procedures were repeated after replacement of the defective SCR. The verification test now produced the required welder peak output test level at a watt-second energy setting 10% less than normal, with a concurrent reduction in pulse width from the required test standard value. Further investigation revealed the replacement SCR to have about one-half ohm lower forward conducting resistance than the original (yet still within SCR manufacturer's specifications), and the original pulse characteristics were restored by adding resistance to the circuit. The system then passed the verification procedure, and the NDT measurements were continued without the serious compromise in data continuity that the SCR replacement effects would otherwise have caused.

A calibration program was developed and employed to provide the necessary assurance that the welding station equipment conformed initially to acceptable performance requirements and maintained known and repeatable operating characteristics. This program is discussed in the following paragraphs.

Two categories of calibration were established. The first was to provide initial certification of the welding equipment by measuring certain basic parameters and recording these for later reference. This permitted the equipment to be returned to its original condition after performance of any extensive maintenance which might be required in the course of the program. Remeasurement of these parameters would then be required only for the extensive maintenance cases, or in cases

where significant variabilities were noted in a second category of more frequently performed calibration measurements. Our choice of parameters in this second category included measurements which were demonstrated to be sensitive indicators of changes occurring either in the Category 1 parameters, or in any other normally stable elements of the welding equipment. Details of NDT transducer calibration are covered in the NDT Instrumentation Development portion of this report.

1. Category 1. Initial Certification Calibration Steps

- a. The actual capacitance of the power supply capacitor bank was accurately measured at the beginning of the study, and no effective changes have been noted in the course of the program.
- b. Measurements were made of the DC resistance of the entire secondary circuit, including the electrodes, and again no effective changes have been noted. Periodic cleaning of the critical electrical connections has helped to maintain this condition.
- c. The repeatability of the welder power supply watt-second meter has been checked against an external 0.25% meter and has shown consistent agreement to within 1%. The meter square law scale has also been checked against our 0.25% meter, and there is agreement within 2%.

- d. The mechanical follow-up characteristics of the welder head were checked for complete freedom of motion. A source of friction was identified and remedied.

2. Category 2. Daily Calibration Steps

- a. During each period of active NDT welding measurement, welding system end-to-end dynamic calibration checks were made. The machine welding pulse peak output and pulse width were measured on a storage oscilloscope using a standard 150 micro-ohm shunt placed between the welding electrode tips. To provide standard, repeatable conditions for this test, the electrode firing force was set to its test condition value using a precision dynamometer force gage, the power supply was set to its test value (with the watt-second meter being checked against a precision DC voltmeter), and the oscilloscope calibrated against a square wave generator measured by an AC meter.
- b. The voltage across the capacitor bank was independently monitored to an accuracy of 0.25%. This measurement was also repeated for each individual weld made during the program.

- c. All of the welding forces were set using standard dynamometer-type electrode force gages. Two of these precision gages are kept at the welding station to provide cross-checks. These have been inter-checked in our laboratory using precision weights to assure gage consistency.

These calibration steps were followed with sufficient care to assure us that the weld stations were operating properly at the values established for each set of welds.

G. WELD MATERIALS SELECTION

The material in widest use for component interconnection is nickel because of its excellent welding properties, particularly with the commonly used lead materials discussed below. Except for unusual cases where nonmagnetic materials (such as alloy 180 and alloy 90) are needed, nickel is universally used. There are several interconnect ribbon or wire sizes in use, but the 0.012 inch by 0.030 inch ribbon appears to have the greatest acceptance and was chosen as the basic interconnect material for the WVS NDT studies.

Four materials — copper, Dumet, Kovar, and nickel — are the most prevalent component lead materials used in the aerospace industry, and are all covered by MIL-STD-1276. This specification is intended for use with component leads intended for welding and contains sufficient quality control provisions to assure the desired consistency for our program. It was agreed upon by cognizant NASA personnel that for this portion of the NDT investigation, the following lead materials would provide adequate experience with the welding combinations most frequently used in industry, with nickel ribbon utilized to represent the predominant interconnect material:

- . 0.012" x 0.030" nickel ribbon
- . 0.017" gold-plated Kovar
- . 0.025" solder-coated copper
- . 0.020" gold-plated Dumet

H. WELD SCHEDULE DEVELOPMENT

1. Weld Strength Profiles

Having chosen interconnect and lead material pairs to be employed in the NDT study, it was next necessary to develop welding machine setting data for each pair, and from these data to select optimum weld schedule values of welding energy and inter-electrode force (at time of welder firing). These weld schedule values are most easily obtained by first developing weld strength profiles for each pair of materials.

A weld strength profile is a method of establishing an optimum weld schedule by an efficient and simplified procedure. The weld strength profile is a plot of weld breaking load versus energy at constant electrode pressure. An example developed during our study is shown in Figure 2. The dependent variable — weld strength — is plotted on one axis and the independent variable — weld energy — on the other. For each of several force settings, a separate curve is plotted. This provides a family of energy versus pull strength curves, the welds identified with any individual curve having been made at the same force setting. In practice, there is usually enough experience available in connection with welding the commonly used materials to allow choice of a small number of strength profile force values for trial. These values are selected in a range giving a high probability of encompassing the optimum weld schedule point sought. The watt-second energy range over which the test welds are to be made can also be chosen roughly from existing experience. This energy range is then divided up to provide a number of discrete, spaced energy values. At each of these energy values

Pull Strength -
Pounds

MATERIAL: NICKEL RIBBON (GD/P)
.012" x .030"

COPPER, SOLDER COATED
(Allen Bradley) .025"

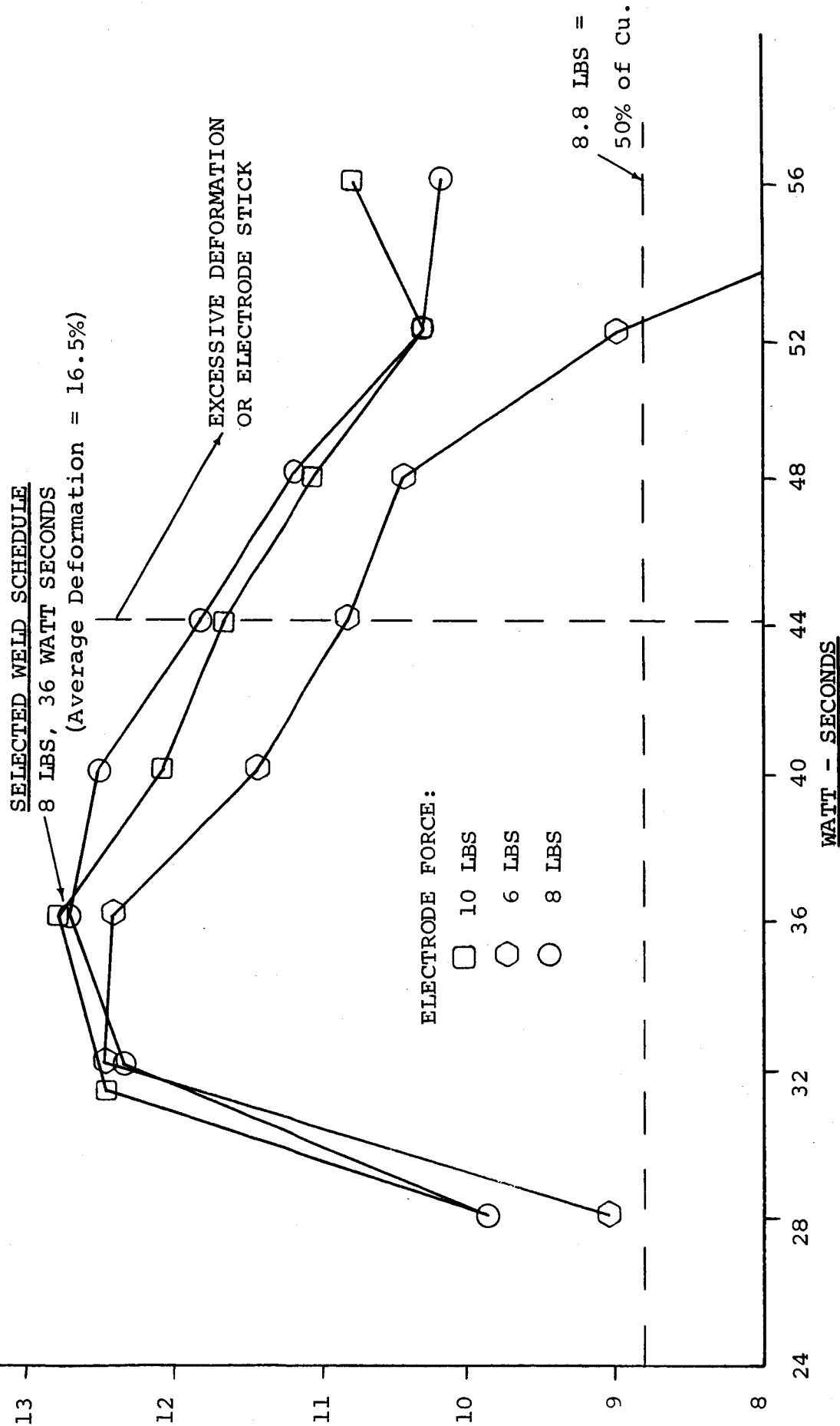


Figure 2
WELD STRENGTH PROFILE

a number of welds are made, pull-tested, the pull strengths averaged, and the average pull strengths are plotted for the welds associated with any set of energy and force values.

The characteristics of these families of constant force weld strength profile curves are then utilized to choose an optimum force and energy value as the individual weld schedule pair for each pair of weld joint materials. Additional weld quality evaluation factors are also utilized in evaluating the optimum weld schedule points from the weld strength profiles. These factors include such weld characteristics as incidence of pits, cracks, voids, excessive expulsion or setdown, and spread of pull strength data for a given parameter set.

2. Weld Schedule Proofing

Verification of each weld schedule selected was made by means of a sample run of 100 welds. As verification, the minimum weld strength in the sample lot of 100 welds was required to be not less than 50% of the average strength computed for the sample. This is in accord with our previous discussion of acceptance criteria in Section 3, C.

I. NDT INSTRUMENTATION DEVELOPMENT

The instrumentation to be used for measurement of the three selected welding attributes — pulse waveform, setdown, and infrared radiation — was developed within the following set of constraints to insure a practical, production line-usable system.

- . Noninterference with the operator - the instrumentation must not interfere with normal welding operation in any way. This meant that the operator's view of the weld area must not be impaired in any manner; the normal operator manipulations of the weld material with respect to the electrodes must not be interfered with; and accessibility of electrodes and other welder parts for maintenance purposes must not be impeded.

- . No effect on welding characteristics - the instrumentation must not interfere with welding characteristics in any manner. This would be of particular concern in instrumenting setdown, where electrode movement must be transduced into voltage without degrading electrode follow-up characteristics.

- . Minimum complexity - in order to facilitate initial installation of instrumentation, calibration, and maintenance, the actual application must be as simple as possible. For instance, in instrumentation of infrared radiation the use of optics could result in an undesired degree of complexity.

The feasibility of using the three selected weld attributes individually and in combination was investigated and quantitative data were obtained which established the degree of correlation between the individual attribute and weld strength. In order to maximize the utility of the data from the measurement program, all three attributes were quantized simultaneously for each sample weld. By so doing, all three measurements could be related to a single weld of known quality and direct relationship to weld quality of different attributes was made possible in the most effective combination.

The following paragraphs describe in more detail the instrumentation that was developed.

1. Weld Voltage Pulse

Measurement of the weld voltage pulse requires care to insure that voltages induced into instrumentation leads by magnetic fields from the large welding currents do not generate misleading results.

In the instrumentation developed for this study, these induced voltages were effectively eliminated by use of twisted pair leads that were attached to the top ends of the electrodes, and by orienting the lead loop up and away from the welder head.

a. Validation of Measurement Integrity

In order to validate the selected instrumentation connections, a reference connection was made directly to the electrode toes adjacent to the weld contact surface. This

reference connection was made with an approximate 1/8 inch loop existing between the solder connections to the electrode toes and the start of the wire twist. Figure 3 illustrates three pulse monitoring points investigated.

The effective magnetic field pickup of the small area reference signal loop was measured independently by a probe consisting of a similar size unbroken test loop held in the same vicinity while welds were being made. The signal generated in the unbroken test loop was found to be negligible. Finally, verification was accomplished by making simultaneous recorded tracings of the instrumentation pickup (at the tops of the electrodes) waveform and the signal from the electrode toes. These were essentially identical, which provided complete verification of the weld voltage pulse instrumentation configuration.

b. Selection of Readout Device

Because of the very rapid, one-time-only-per-weld characteristic of the weld voltage pulse, a storage-type oscilloscope was selected for readout. A Tektronix 564 was chosen for this purpose since it provided a dual trace capacity for simultaneous monitoring of two NDT instrumentation signals. The oscilloscope single-sweep was triggered for each weld by a signal derived from the regular welder firing microswitch circuit.

c. Calibration Procedure

A 150 micro-ohm shunt was placed between the electrodes to provide a standard reference load for calibration

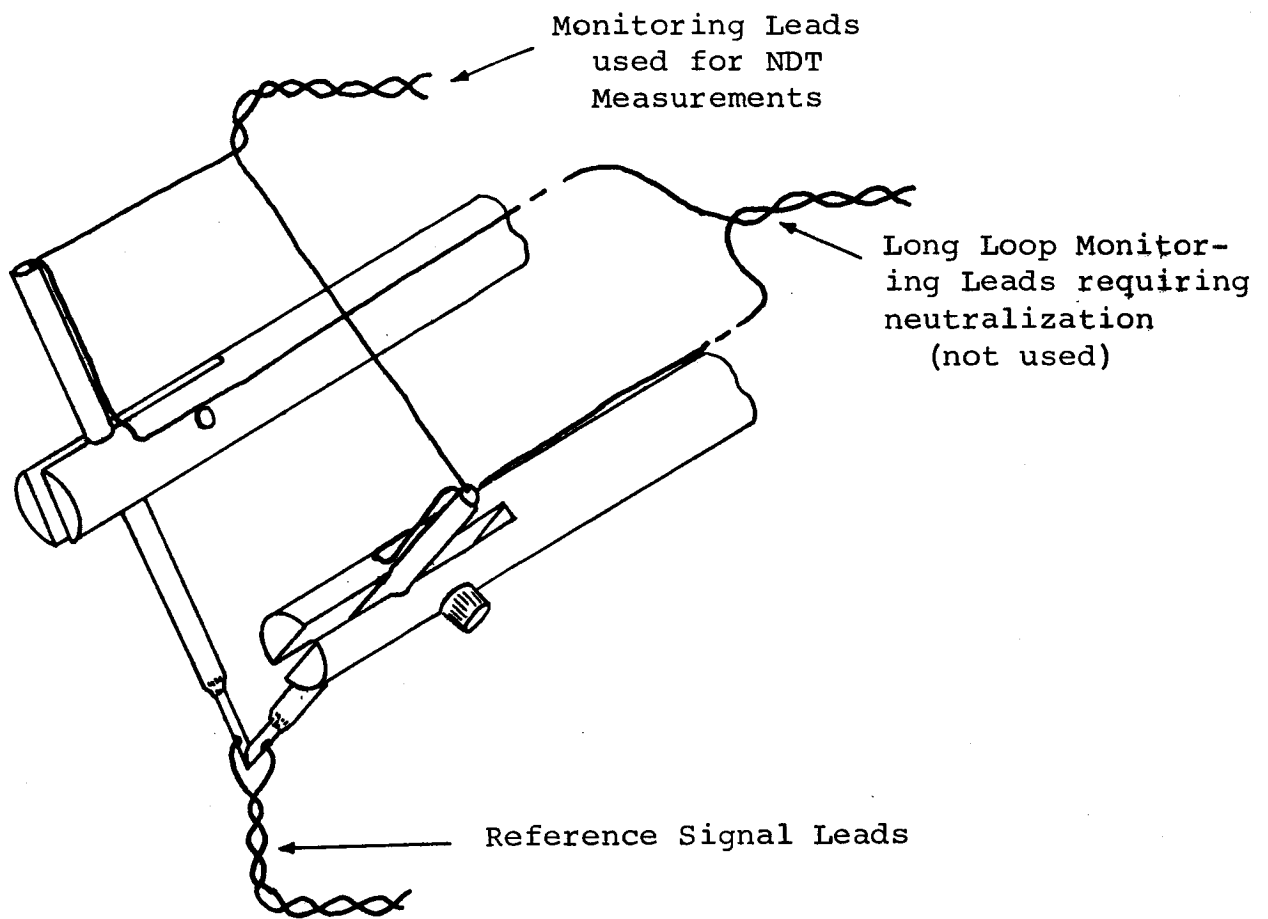


Figure 3
LOCATIONS OF WELD PULSE
MONITORING AND REFERENCE LEADS

purposes. The correct amplitude of weld voltage pulse that should appear across the 150 micro-ohm shunt was determined for each watt-seconds schedule value. The voltage measured across the shunt was then used to verify proper system operation for each weld schedule used.

2. Infrared Radiation

The basic requirement in instrumenting the infrared signature of the weld joint formation was to transduce the infrared energy into a usable signal voltage. A number of approaches were evaluated as possibilities, among them the following:

- . Use of a single infrared detector of adequate size and sensitivity, without optics, located above and between the electrodes.
- . Use of fiber optics to convey the IR from the immediate weld area to a conveniently remote detector.
- . Use of an optical system to permit concentration of IR energy at a conveniently located detector.
- . Use of cryogenic equipment to achieve adequate detection sensitivity.

More detailed evaluation of each of these approaches suggested that because of its simplicity, the first approach for laboratory investigation should be to provide as close to the weld joint as feasible, large solid-angle coverage of the weld heated areas without use of focusing optics.

It was estimated from knowledge of the material properties that the peak temperature range of welds under investigation would be approximately 1350° to 1750° Kelvin. In our evaluation of thermal characteristics of the weld, it was also recognized that spectral emissivities for the weld materials could vary as a function of surface conditions of the same material type. However, the experimental NDT results have not indicated this to be a serious problem for our conditions of measurement.

A number of specific IR detector materials with possibly suitable characteristics were considered. The detector types reviewed and the pertinent operating characteristics are tabulated in Table 2.

From this list, two detector types were selected for detailed evaluation. The silicon photovoltaic cell was chosen because of its large sensitive area which circumvented the need for optics or precise positioning. On the other hand, in order to provide adequate coverage in the longer IR wavelengths with good sensitivity, the lead sulfide photoconductive cell was also considered. Because of its smaller sensitive area, the lead sulfide cell required an optical support system.

Our detector type evaluation, weighing all factors, has resulted in the choice of the Hoffman N120CG-11L photovoltaic silicon cell with a sensitive area of 0.375" by 0.75". It is mounted on the weldhead directly above the welding electrodes, as shown in Figure 4, and is covered with an IR transmitting filter to minimize the effect of ambient light conditions on cell output. Connection to the readout instrument is again through twisted pair conductors to minimize stray magnetic field pickup.

Cell Type	Peak Energy Point λ_{\max} Micron	Range of 50% Max. Energy λ 's	D* at 300°K
Si PT	.9	.6 - 104	5×10^{11}
Ge PT	1.55	.4 - 1.7	5×10^{12}
Si PV	.9	.6 - 1.04	2.3×10^{12}
PbS PC	2.4	1.3 - 2.8	1×10^{11}
InAs PC	3.6	2.5 - 3.7	2.9×10^9
PbSe PC	4.0	1 - 5	2.0×10^9
1720°K ⁽¹⁾ _A	1.7 ⁽¹⁾	1.2 - 3.2 ⁽¹⁾	-----
1360°K ⁽¹⁾ _B	2.1 ⁽¹⁾	1.4 - 3.7 ⁽¹⁾	-----

(1) Black body radiation for estimated maximum weld temperatures reached by Ni-Kovar (A) and Ni-Cu (B) pairs.

NOTE: PT = Phototransistor

PV = Photovoltaic

PC = Photoconductive

Table 2
CRITICAL IR CELL PARAMETERS

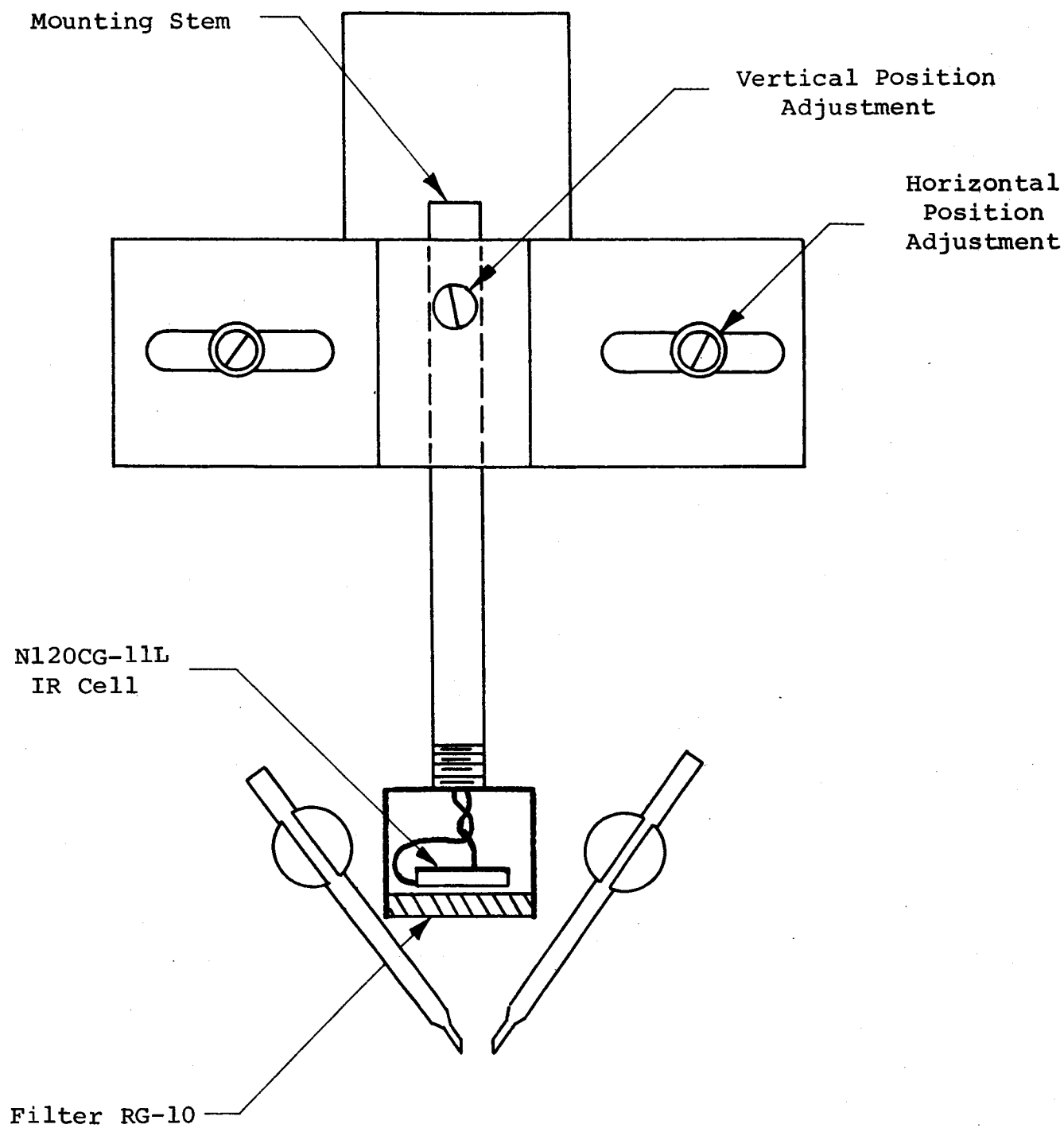


Figure 4
IR DETECTOR ASSEMBLY

a. Readout Instrumentation

As with the weld voltage pulse, the infrared radiation occurring during the time the weld is made is a transient phenomenon. For this reason, the second trace of the dual trace Tektronix 564 was selected as the readout device. Vertical amplifier gain of the Tektronix is adequate to eliminate the need for preamplification and the use of its image storage feature permits detailed examination of the waveform and photography for future reference as required.

b. Calibration Procedure

For calibration of IR instrumentation, a miniature (0.030" diameter) tungsten filament bulb, operated at a predetermined, precisely monitored current value, is used as a reference source. A fixture was designed which places the bulb in a fixed position relative to the IR sensor with the filament parallel to the plane of the sensor. This position is between the welding electrodes at the same location where a weld would normally be made.

3. Setdown

The third welding attribute to be instrumented was "setdown." For the purposes of this discussion, setdown includes both embedment and indentation. Embedment is the distance that lead and ribbon are displaced into each other, while indentation is the distance that electrodes penetrate leads and ribbon. The actual setdown of concern to this investigation is the change in electrode separation while the weld

is being made. This change is measured as the difference between two positions of the movable electrode. The first is the electrode position just at the time firing force is reached, but immediately prior to application of weld energy. The second electrode position is that reached after the weld process is completed, but prior to removal of weld force. This change is referred to in this discussion as dynamic setdown.

A feasibility study was made of a variety of transducers including linear differential transformers, low-friction infinite resolution potentiometers, light-actuated frictionless potentiometers and mechano-electronic devices (such as the RCA 5734 tube), and strain gages. Among the requirements given prime consideration in the transducer study were linearity, hysteresis, high output level, large dynamic range, low spring rate or friction, and low mass.

a. Transducer Selection

A miniature cantilever beam assembly embodying the above requirements was developed in our laboratory. A silicon piezo-resistive strain gage was selected as being the most suitable for measurement of beam deflection. The final transducer design consists of four strain gages attached to a beam — two in tension mode and the other two in compression mode — and electrically connected in a full-bridge for instrumentation. The strain gages were provided by and mounted to our beam design by Manning Instruments, Inc. The strain gage beam is clamped between metal mounting blocks which support and position the beam perpendicular to the movable electrode holder. The motion of the electrode holder during the welding process deflects the

cantilevered beam as setdown occurs, producing the measured change in strain gage bridge output. The inter-electrode force is nearly constant during this period of measurement, so no electrode bending change errors are introduced.

The length of the beam and location of the strain gages on the beam were adjusted experimentally to attain maximum sensitivity commensurate with required beam bending force. The resulting instrumentation provides an accurate output of 35 millivolts per mil of movable electrode tip travel.

In order to ascertain that the setdown instrumentation would not affect welder operation, sample welds were made both with and without the instrumentation. Analysis showed that a force of approximately 0.35 pounds was needed to deflect the beam through the 12 mil setdown range normally encountered. The sample welds showed no discernable difference between the "with transducer" and "without transducer" samples in terms of either average pull strength (\bar{x}) or range of pull strength values. As a result, we concluded that no degradation of electrode follow-up characteristics was incurred by use of the instrumentation.

Since the setdown transducer will sense any movable electrode holder travel, system bending must be considered in any measurement of weld dynamic setdown.

System bending, up to the point weld force is reached, represents a bias which establishes the strain gage initial output value, to which the final dynamic setdown measurement is referenced. It was therefore necessary for us to

determine (a) whether system bending magnitude for any given force setting was repeatable and (b) the actual magnitude of bending as sensed by the transducer relative to applied force.

The resolution of these unknowns required that the fixed electrode holder be instrumented with a strain gage beam in a manner identical to that previously described for the movable electrode. Figure 5 illustrates the mechanization of the required measurements and the instrumentation utilized. The dial gage shown was used, in conjunction with precision leaf gages, for strain gage beam deflection calibration.

Repeatability of system bending relative to welding force was demonstrated by measuring the fixed electrode transducer output at force settings in increments of one pound over the range from five to ten pounds. The force at each setting was removed and reapplied five times and trace overlays corresponding to transducer output were recorded on a Tektronix Type 564 storage oscilloscope. Figure 6 is a drawing made directly from the oscillograph and shows five trace overlays at each of six different force settings (five to ten pounds inclusive), and demonstrates acceptable system bending repeatability.

Once bending repeatability had been established, the amount of system bending was derived relative to the applied weld force.

The fixed electrode holder instrumentation was utilized several times during the program to measure actual force at the instant of welding. This measurement has merit also for process control application.

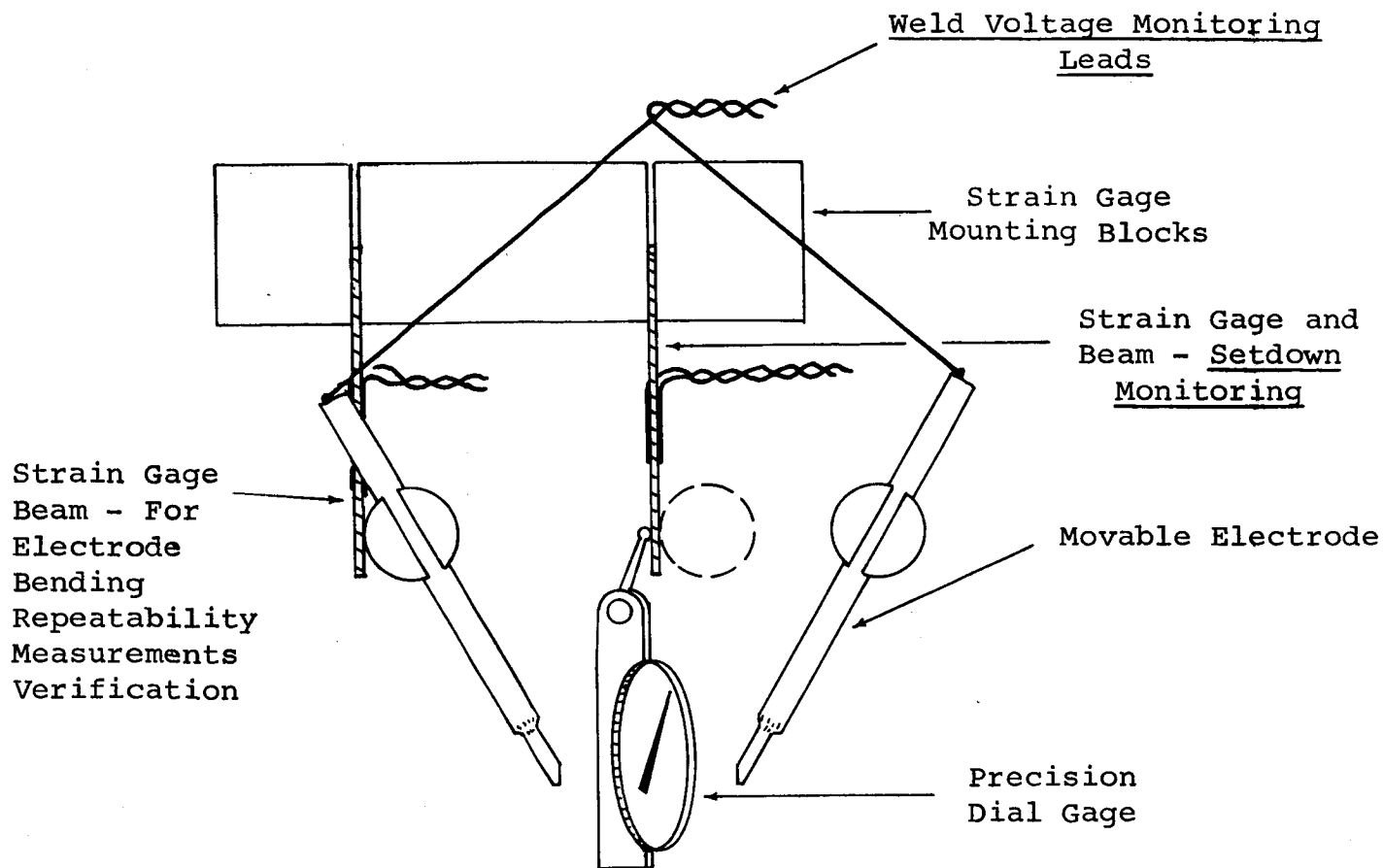


Figure 5

WELDER HEAD SETDOWN INSTRUMENTATION
MONITORING POINTS

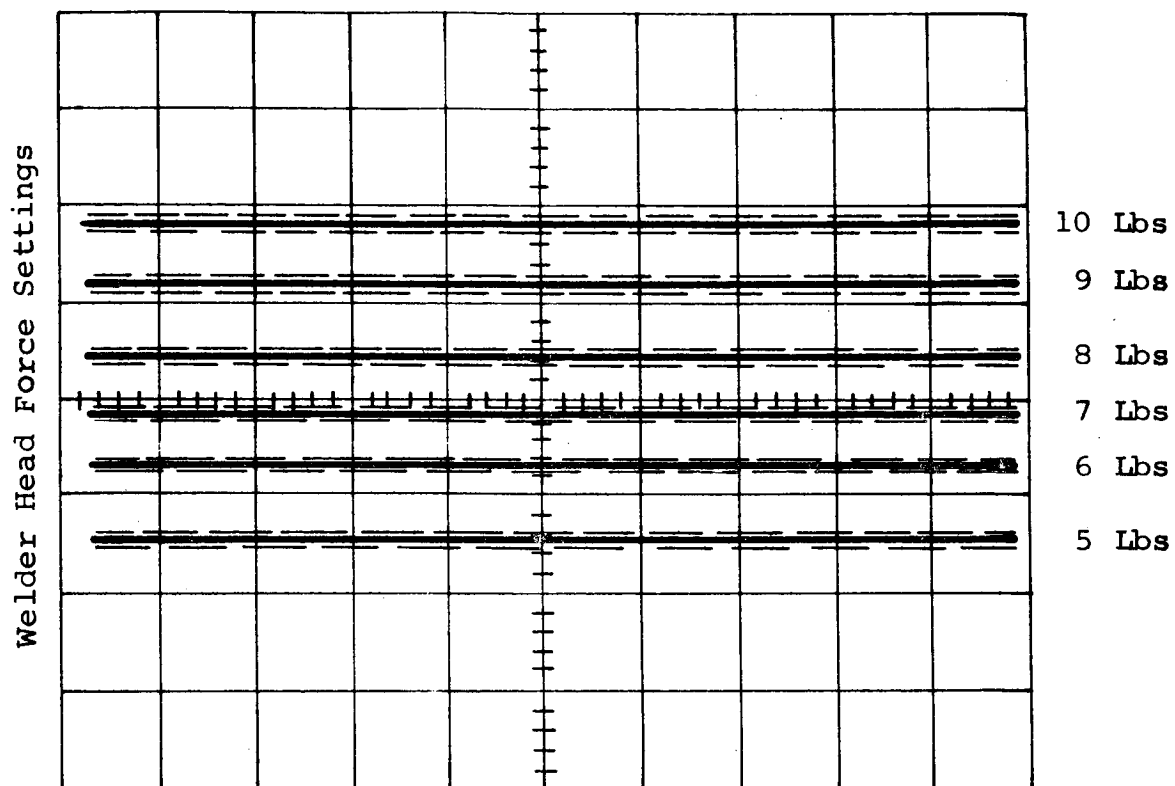


Figure 6

STRAIN GAGE OUTPUT OVERLAY SYSTEM
BENDING REPEATABILITY INVESTIGATION

b. Readout Instrumentation

Because of the range of values available from the transducer bridge (35 mV/mil), a digital voltmeter capable of reading in millivolts was chosen for readout of setdown information. A Digitek Model 201 was available in the WVS laboratory and proved adequate for the purpose. Figure 7 shows the complete welder head instrumentation configuration used to obtain our experimental results.

c. Calibration Procedure

Because of the bending characteristics of the electrodes and holders, an indirect relationship exists between transducer movement and weld setdown. For this reason a calibration curve was generated to relate transducer bridge output to true distance between electrode tips. The calibration curve was generated by inserting shims between the electrodes and measuring bridge output at a specific weld-force setting. Seven readings were taken at increments of shim thickness, and the mean of each set of readings used to establish a point on the calibration curve. A typical calibration curve is presented in Figure 8. Insofar as dynamic setdown accuracy is concerned, setdown instrumentation is calibrated at the specific welding force used, and any system bending is automatically accounted for in the calibration procedure and valid readings are assured.

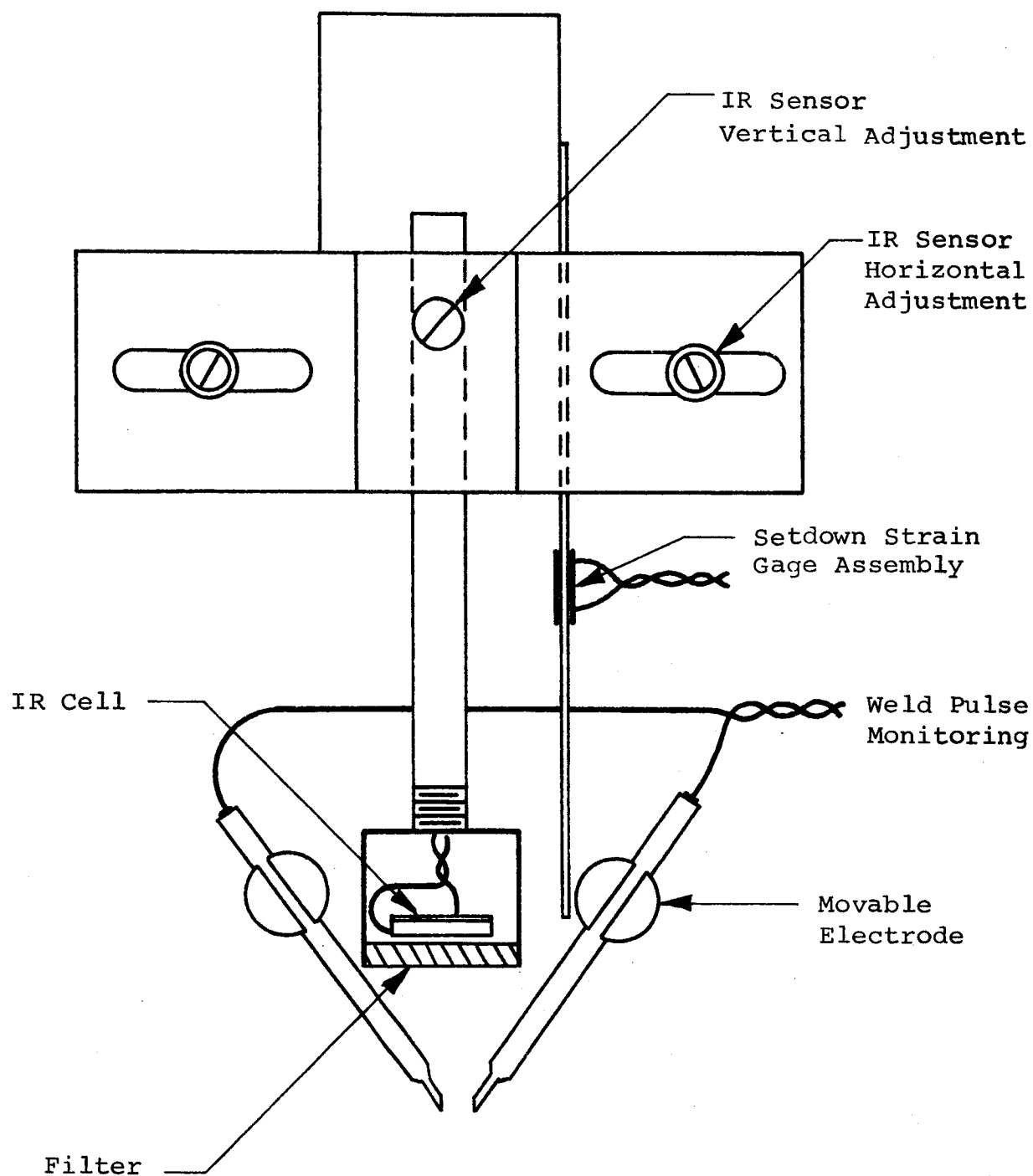
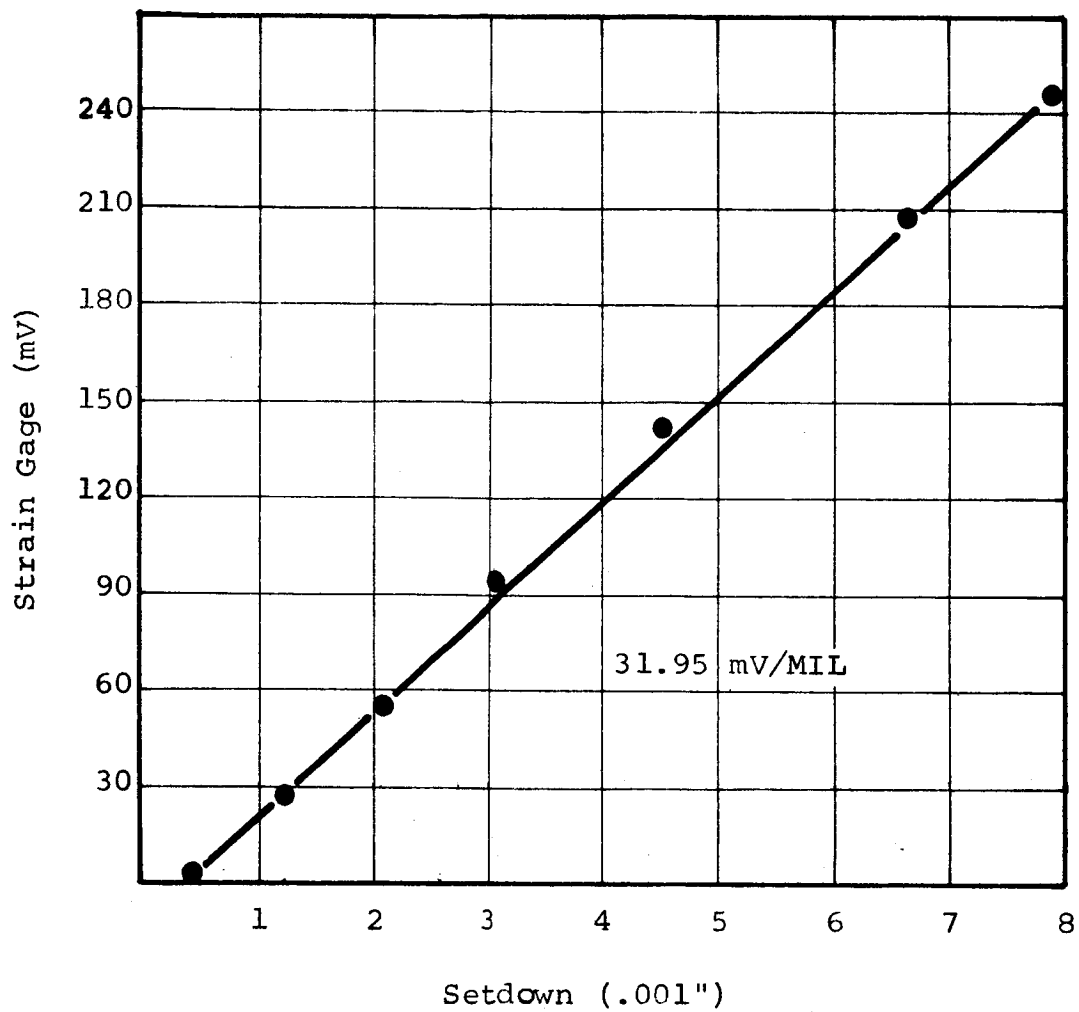


Figure 7

COMPLETE WELDER HEAD
NDT INSTRUMENTATION



NOTE: Final beam length was set to give 35 mV/MIL

Figure 8

TYPICAL STRAIN GAGE CALIBRATION CURVE

J. EXPERIMENT DESIGN

In order to assess the potential effectiveness of our NDT instrumentation, a series of measurement programs was conducted on selected pairs of weldable material. The construction of a very large number of welds at optimum weld schedule (in the hope of identifying any poor ones) was rejected because the normal yield of "bad" welds would be small and there would be little assurance that NDT measurements from defective welds would provide reliable differentiating data.

The basic approach chosen was to intentionally deviate from optimum welding conditions in a controlled manner by duplicating situations that might typically occur in production. This would ensure the production of "bad" welds in a manner and in quantities that would make evident the most likely causes and the most sensitive NDT attributes. A discussion of the steps taken to implement these objectives follows.

1. Control Groups

For each weld material pair, an optimum weld schedule was first established by the pull-strength energy-profile method (weld strength profile, discussed in Section G above). A control group of welds was then fabricated under ideal conditions. The control groups consisted of fifty welds each, for which all NDT measurements and pull strengths were recorded.

The control group measurement data provided us with a comparison baseline for each NDT parameter by defining the measurement

distribution characteristics that can be anticipated from welds constructed under optimum schedule and process control conditions.

2. Deviation Groups

In addition to the control group, many test groups of five welds each were constructed in which controlled deviations in positioning, material, schedule and other process elements were introduced. The variables used simulated the most frequent causes of weld defects, as indicated by WVS experience, and as identified by cognizant personnel from other organizations contacted during this study program. The purpose of the variables groups then is:

- . to explore the tolerance of the selected welded material pairs to the induced variables,
- . to provide an indication of the resolution of our NDT instrumentation relative to the detection of defective welds, and
- . to evaluate the sensitivity of our NDT instrumentation as an indicator of deviations in weld process control.

An IBM 1130 Computer was used to perform the analysis operations on each set of weld attribute measurements. The statistical criteria employed are typical of those currently used in the aerospace industry for process analyses.

The statistical criteria and formulas used for the information presented in this report are listed below:

- . Arithmetic mean = $\bar{x} = \frac{\sum x}{n}$
where n is the number of welds
- . Standard deviation = $\sigma = \sqrt{\frac{\sum (x - \bar{x})^2}{n - 1}}$
- . Total range = R, difference between the largest and smallest measurements.

The categories of welding process induced variables examined by WVS in this study were:

- Offset - controlled mispositioning of weldments between electrode faces.
- Shorts - welding current shunted around weldment by wire or ribbon contact with opposite electrode.
- Material Position Reversed - weld pair rotated 180° between electrodes, resulting in opposite welding polarity to that required by the weld schedule.
- Incorrect Material - substitution for correct wire or ribbon material of incorrect material of similar appearance.
- Wrong Weld Schedule - application of electrode forces or welder energy values differing from proper weld schedule.

3. Acceptability Criteria

For purposes of this study, and for the particular materials tested, a weld has been considered "good" if the dynamic set-down is less than 35% of the total material thickness, and the pull strength exceeds 50% of the \bar{x} value for the specific control test group welds. These values are practical and most typical of those accepted by industry and therefore appropriate for this study.

On a weld-by-weld basis and for the selected materials tested, it was decided that our instrumentation should reject any weld that failed to meet the above criteria and conversely should accept every weld that did. During the forthcoming aerospace production line NDT prototype equipment evaluation, criteria and limits will be developed experimentally to fit particular production requirements.

The individual weld data results of each controlled experiment were layed out on matrix charts. The ranges of measured values from the control groups are presented for pull strength and the three NDT parameters. These data ranges establish the acceptance limits for the deviation group welds. Each weld is numbered. The completed charts were used to evaluate the NDT effectivity of our instrumentation.

The summary results of the matrix data evaluations were then presented in "truth tables." In these truth tables each controlled variable is identified by number and description, Columns 1 and 2, respectively. Column 3 identifies the individual weld by a number which corresponds to an identical weld number for the particular variables group contained on the appropriate matrix chart. Columns 4 through 6, corres-

ponding to the measured attributes (Setdown, Infrared and Weld Waveform), are provided to allow assignment of the test results to each weld.

The results of the individual weld measurements are summarized and evaluated in the remaining columns. Column 7 states whether the weld was accepted or rejected by the instrumentation regardless of the authenticity of the evaluation. Column 8 lists the reason for weld reject in the event a defective weld was fabricated as determined by the Setdown instrumentation or subsequent pull strength measurement. In the event a weld was rejected by the instrumentation but was good by our criteria (i.e., >50% of the control group average pull strength and >35% Setdown), notation to that effect is made in the Weld Failure column.

The validity of the NDT test result is indicated in Column 9. Thus, if the NDT instrumentation accepts a weld that meets the basic pull strength and setdown requirements, or if it rejects one that does not, the test result is indicated as valid. Conversely, if the instrumentation rejects a weld that is good by our criteria or accepts a weld that is bad, the NDT result is indicated as not valid.

The Process Control Monitor entries in Column 10 are designed to indicate the sensitivity of the NDT instrumentation to deviations from optimum welding conditions. The NDT system was considered sensitive if two or more false readings were obtained from any of the measured attributes in their respective variable group. Where the materials being welded and the NDT instrumentation were not sensitive to the particular variable involved, a "materials not sensitive" notation was made. Where defective welds were fabricated and the Process Control

aspects of the NDT instrumentation were not sensitive to the cause, a not valid condition is indicated in Column 10.

The three measurement result columns, 4, 5 and 6, utilize the symbols T for "true" and F for "false." A true, or acceptable value for a given weld parameter measurement is here taken as one lying within the range of values obtained for this parameter from the weld control group NDT measurements. A false, or unacceptable value, is one lying outside the NDT control group range.

In addition, for the setdown column, a symbol, |R|, is used to indicate that the weld is to be rejected on an absolute criterion basis, regardless of other data. To provide a reasonable limit value for our study (to be revised as necessary to fit later production evaluation requirements) the |R| value for setdown was chosen to reject anything over 35%, which, in fact, is a widely used maximum limit value in the industry. The NDT prototype instrumentation will have an additional |R| feature for cases where the welder power supply pulse polarity control switch is in the wrong position. This condition would result in an inverted Weld Pulse signal and will be indicated as a process-out-of-control condition.

A summary of the conditions for acceptance or rejection of a weld follows:

REJECTION CRITERIA: any weld with over 35% dynamic
 setdown

or, any weld with pull strength
 less than 50% of x

or, any weld produced with reverse polarity setting

or, any weld yielding any two or more "FALSE" weld parameter signals; i.e., any detected signal outside the range of values obtained from the control group NDT measurements.

ACCEPTANCE CRITERIA: any weld with less than 35% dynamic setdown

and, more than 50% pull strength

and, proper weld polarity setting

and, any two or more "TRUE" weld parameter signals; i.e., any detected signal inside the range of values obtained from the control group NDT measurements.

To summarize, the following is the pertinent information relative to the experiments discussed in the next section:

Welder Type:	Capacitor discharge
Electrode Type:	RWMA 2, Copper (2 each)
Electrode Angle:	70° (included)
IR Sensor:	Hoffman N120CG-11L solar cell, with Schott RG-10 filter
IR Readout:	Tektronix, Type 564 storage oscilloscope with 3A72 and 2B67 plug-ins

Weld Pulse	
Monitoring Point:	Electrode tops
Readout:	Tektronix, Type 564 storage oscilloscope with 3A72 and 2B67 plug-ins
Setdown Transducer:	Manning Instruments strain gage beam (full bridge)
Setdown Readout:	Unified Systems Model 201 Digital Voltmeter

Four experiments were designed based on the welding materials pairs listed below:

Experiment B-7:	Nickel ribbon to copper wire
Experiment B-8:	Nickel ribbon to Kovar wire
Experiment B-9:	Nickel ribbon to Dumet wire

The results of the above experiments and the measurement data obtained are presented in the following section of this report.

K. EXPERIMENT RESULTS

Detailed results of each of the four NDT instrumentation evaluation experiments are presented in the following paragraphs.

1. Experiment B-7

The background information pertinent to this specific experiment is tabulated below:

Material:	0.012" x 0.030" type A nickel ribbon
	0.025" oxygen-free high conductivity (OFHC) copper, solder coated
Average Breaking Pull-Strength of Materials:	Nickel - 23.0 lbs
	Copper - 18.8 lbs
Weld Schedule.	8 lbs, 36 watt-seconds
Pulse:	Long

The copper wire employed in this investigation was obtained from 1/4 watt resistors supplied by a major manufacturer and no attempt was made to control or select lead material relative to dimension, solder coating thickness, or composition. This wire material is known to contain oxygen-free, high conductivity copper (OFHC), and was chosen by WVS for its proven weldability and uniformity characteristics (in contrast to other common difficult-to-weld and variable materials, such as electrolytic tough pitch copper).

Distribution of the measured weld parameters and pull strengths for the control group of welds at optimum weld schedule are illustrated in histographic form in Figures 9, 10, 11 and 12. The statistical information is shown in Table 3.

The NDT measurement results for the complete experiment are shown in Figure 13. The range of pull strength values and weld parameter measurements for the control groups are represented by the solid black bars in the control group row of the matrix chart, Figure 13.

The test configurations for the various welding condition groups are identified in the first column of Figure 13. Individual plotted parameter values are accompanied by an adjacent number that identifies the specific weld in each group of five.

The following are the definitions used in this experiment for REJECT, FALSE and TRUE weld parameter signals.

Setdown:

REJECT |R| - any dynamic setdown measurement greater than 12.5 mils (thousandths of an inch). This signal, by itself, is an absolute cause for weld rejection.

FALSE - any setdown falling below the lower limit of the control group range (less than 5.4 mils).

TRUE - any setdown in the range from 5.4 mils to 12.5 mils.

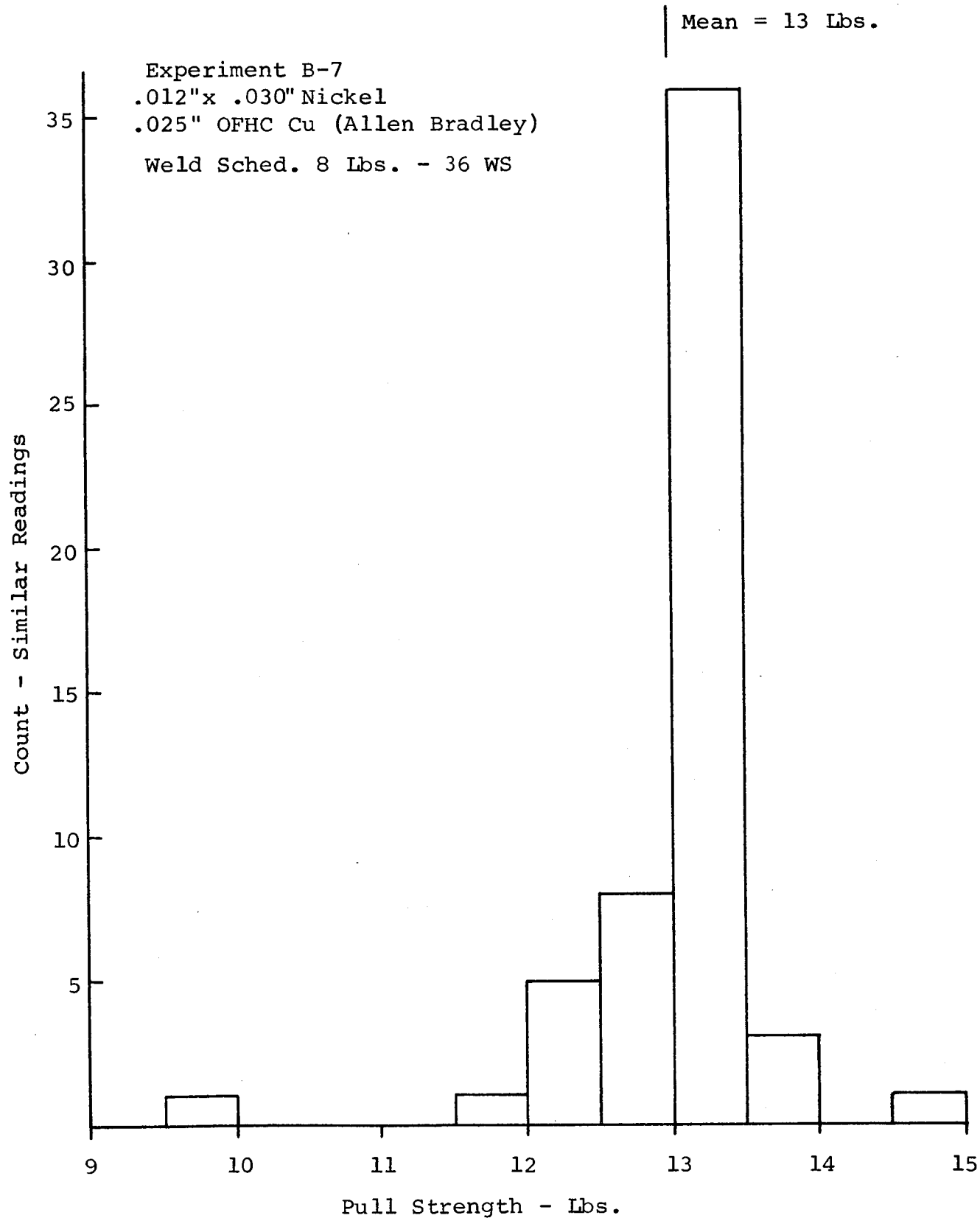


Figure 9

PULL STRENGTH DISTRIBUTION

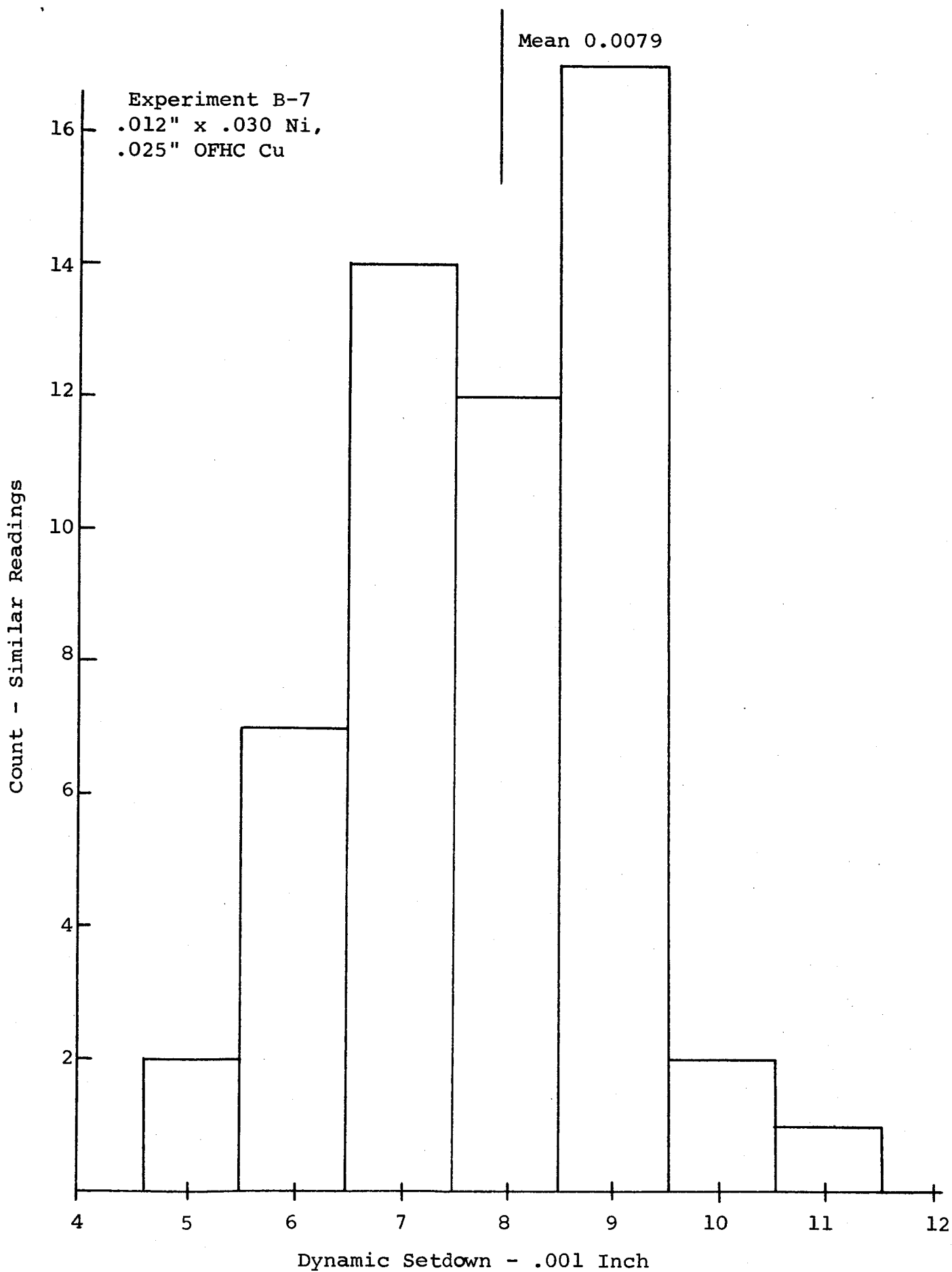


Figure 10
DYNAMIC SETDOWN DISTRIBUTION

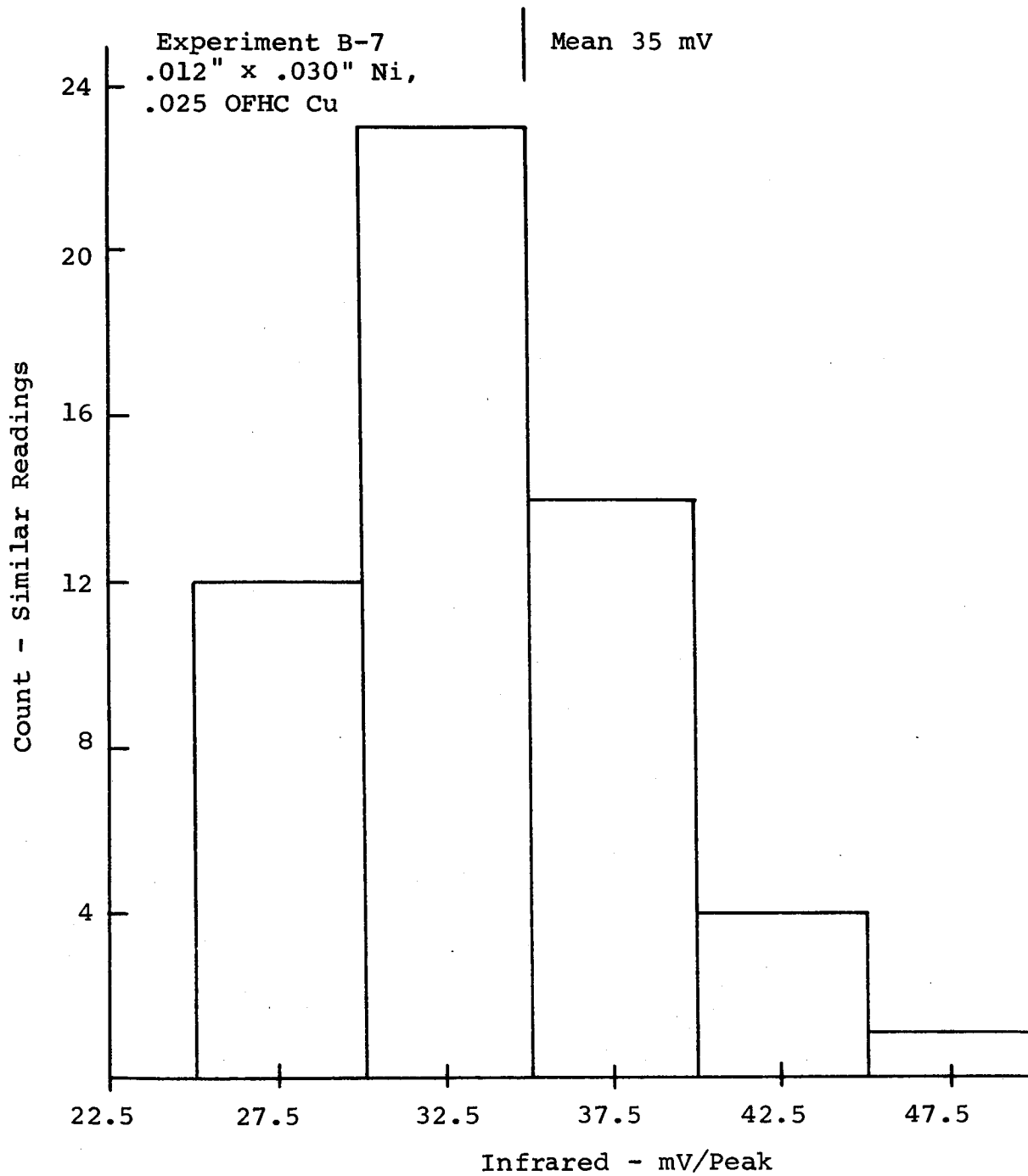


Figure 11

INFRARED PULSE AMPLITUDE
DISTRIBUTION

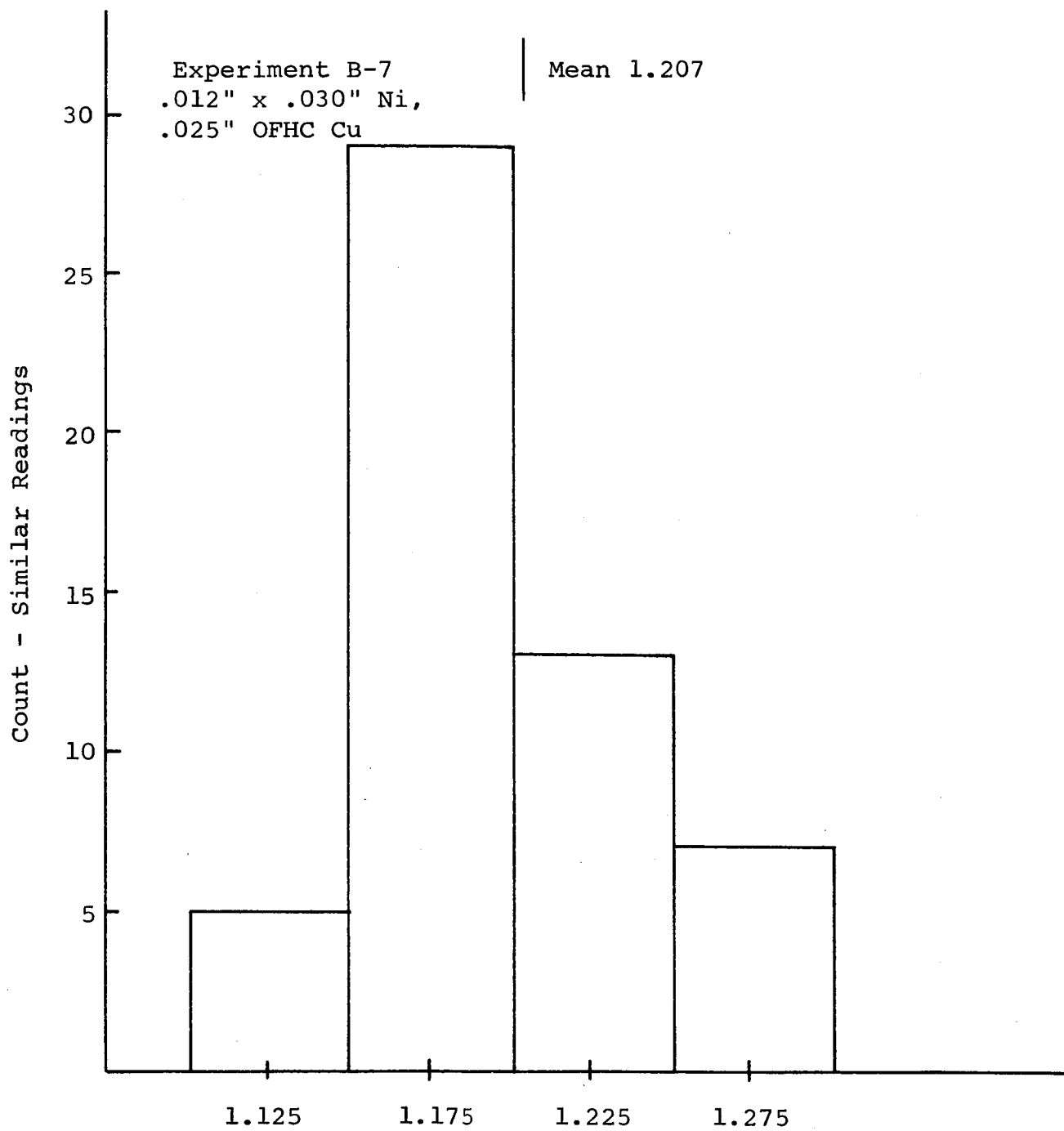


Figure 12

WELD VOLTAGE WAVEFORM - V/PEAK VALUE DISTRIBUTION

ATTRIBUTE	\bar{X}	σ	Range
Pull Strength (lbs)	13	.626	4.8
Setdown (.001")	7.9	1.2	5.9
Infrared (mV) Cell Output	35	5.3	20.0
Weld Waveform Peak Value (mV)	1207	36.0	130.0 mV

.012" x .030" Nickel
.025" OFHC Cu (Allen Bradley)
Weld Schedule 8 lbs. - 36 WS

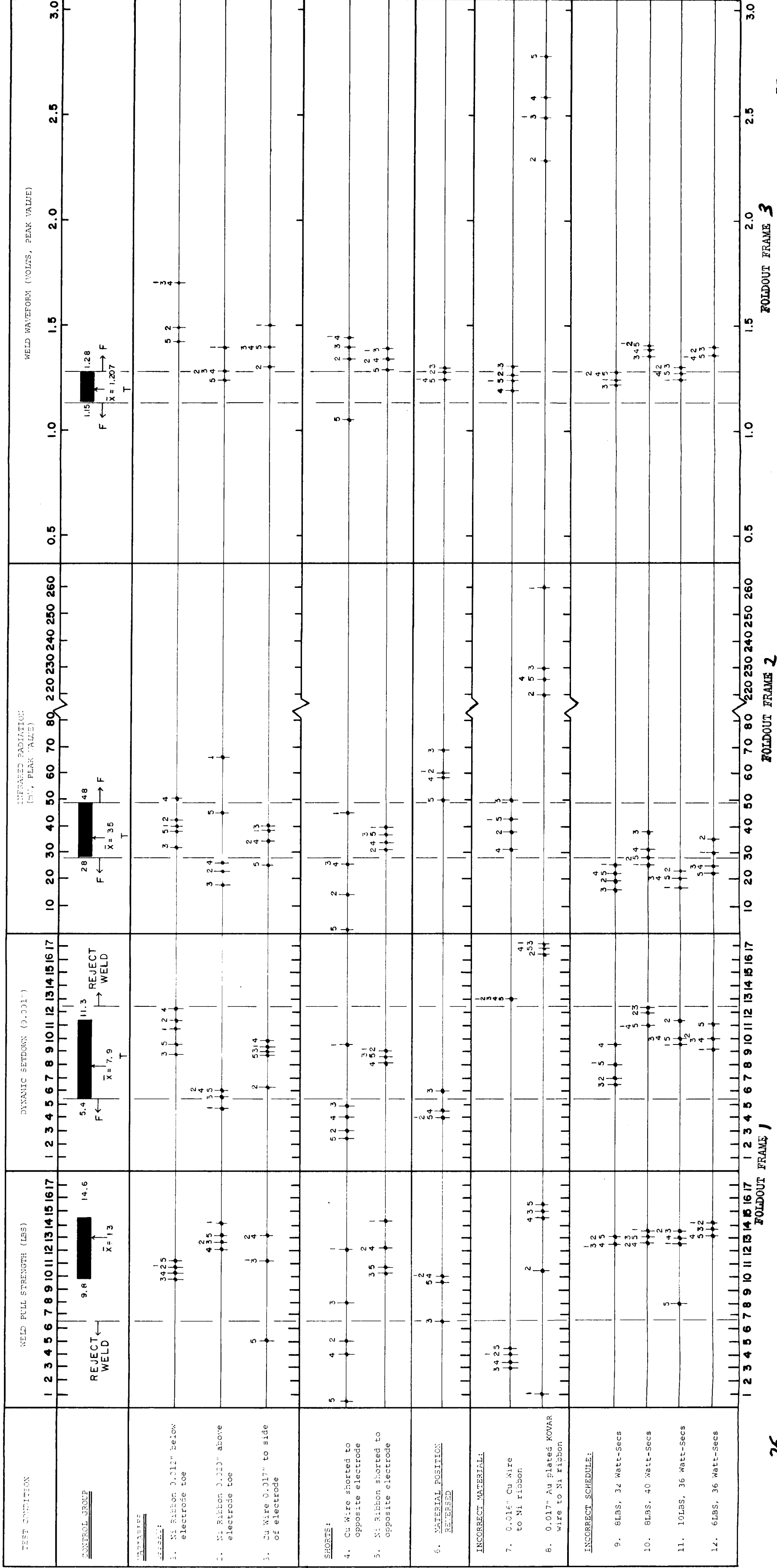
Table 3

CONTROL GROUP DATA SUMMARY

Experiment B-7

FIGURE 13

NDT RESULTS FOR 0.012" X 0.030" NICKEL RIBBON - 0.025" OFHC COPPER WIRE WELDS (EXP. B-7)



FOLDOUT FRAME 2

FOLDOUT FRAME 3

FOLDOUT FRAME 1

Infrared Radiation:

FALSE - any signal above or below the control group range; i.e., less than 28 mV or over 48 mV.

TRUE - any signal inside the control group range.

Weld Pulse:

FALSE - any signal above or below the control group range; i.e., less than 1.15V or over 1.28V.

TRUE - any signal inside the control group range.

A Truth Table (Table 4) was derived from the data presented in the matrix chart (Figure 13) to identify the acceptable and defective welds and evaluate NDT effectivity.

It is highly significant to note that each time a "bad" weld occurred, it was detected by the NDT instrumentation, and in no instance was a "bad" weld accepted.

There were, however, some instances where "good" welds were rejected by our instrumentation. However, in all instances the weld groups were flagged by two or more rejections in one or more NDT channels as being outside process controlled limits. These are discussed below.

Grp.	Variables		Weld No.	Setdown	Infra-red	Weld Wave-form	Individual Weld NDT Result	Weld Failure		NDT Test Valid		Process Control Monitor Valid
	No.	Title						Pull S. <6.2#	Setdn. >35%	YES	NO	
1		Ni ribbon 0.012" below electrode toe	1	T	T	F	Accept			X		Yes
			2	T	T	F	Accept			X		
			3	T	T	F	Accept			X		
			4	T	F	F	Reject	Weld/OK	Weld/OK		X	
			5	T	T	F	Accept			X		
2		Ni ribbon 0.020" above electrode toe	1	F	F	F	Reject	Weld/OK	Weld/OK		X	Yes
			2	T	F	T	Accept			X		
			3	T	F	T	Accept			X		
			4	T	F	T	Accept			X		
			5	T	T	T	Accept			X		
3		Cu wire 0.017" to side of electrode	1	T	T	F	Accept			X		Yes
			2	T	T	F	Accept			X		
			3	T	T	F	Accept			X		
			4	T	T	F	Accept			X		
			5	T	F	F	Reject	X		X		
4		Cu wire shorted to opposite electrode	1	T	T	F	Accept			X		Yes
			2	F	F	F	Reject	X		X		
			3	F	F	F	Reject	Weld/OK			X	
			4	F	F	F	Reject	X		X		
			5	F	F	F	Reject	X		X		

Table 4

NDT MEASUREMENT TRUTH TABLE

Grp.	Variables		Weld No.	Setdown	Infra-red	Weld Wave-form	Individual Weld NDT Result		Weld Failure		NDT Test Valid		Process Control Monitor Valid
	No.	Title									YES	NO	
5		Ni ribbon shorted to opposite electrode	1	T	T	F	Accept				X		Yes
			2	T	T	F	Accept				X		
			3	T	T	F	Accept				X		
			4	T	T	F	Accept				X		
			5	T	T	T	Accept				X		
6		Material position reversed	1	F	F	T	Reject	Weld/OK	Weld/OK			X	Yes
			2	F	F	T	Reject	"	"			X	
			3	T	F	F	Reject	"	"			X	
			4	F	F	T	Reject	"	"			X	
			5	F	F	T	Reject	"	"			X	
7		0.016" Cu Wire to Ni ribbon	1	R	T	T	Reject	X	X		X		Yes
			2	R	T	T	Reject	X	X		X		
			3	R	F	F	Reject	X	X		X		
			4	R	T	T	Reject	X	X		X		
			5	R	T	T	Reject	X	X		X		
8		0.017" Au plated Kovar wire to Ni ribbon	1	R	F	F	Reject	X	X		X		Yes
			2	R	F	F	Reject		X		X		
			3	R	F	F	Reject		X		X		
			4	R	F	F	Reject		X		X		
			5	R	F	F	Reject		X		X		

Table 4

Grp. No.	Variables		Weld No.	Setdown	Infra- red	Weld Wave- form	Individual Weld NDT Result	Weld Failure		NDT Test Valid		Process Control Monitor Valid
	Title							Pull S. <6.2#	Setdn. >35%	YES	NO	
9	8 Lbs, 32 WS		1	T	F	T	Accept			X		Yes
			2	T	F	T	Accept			X		
			3	T	F	T	Accept			X		
			4	T	F	T	Accept			X		
			5	T	F	T	Accept			X		
10	8 Lbs, 40 WS		1	T	F	F	Reject	Weld/OK	Weld/OK		X	Yes
			2	T	T	F	Accept			X		
			3	T	T	F	Accept			X		
			4	T	T	F	Accept			X		
			5	T	T	F	Accept			X		
11	10 Lbs, 36 WS		1	T	F	T	Accept			X		Yes
			2	T	F	F	Reject	Weld/OK	Weld/OK		X	
			3	T	F	F	Reject	Weld/OK	Weld/OK		X	
			4	T	F	T	Accept			X		
			5	T	F	T	Accept			X		
12	6 Lbs, 36 WS		1	T	T	F	Accept			X		Yes
			2	T	T	F	Accept			X		
			3	T	F	F	Reject	Weld/OK	Weld/OK		X	
			4	T	F	F	Reject	Weld/OK	Weld/OK		X	
			5	T	F	F	Reject	Weld/OK	Weld/OK		X	

a. Group 1, Weld #4

This weld was satisfactory in pull strength, but was rejected on infrared output and upon weld waveform. As is evident from the matrix chart, all of the welds for this group lay well outside the upper limit allowed for weld waveform. In production, such repeated rejections would flag an operator or module layout problem. This type of process control sensitivity will be investigated further in the production NDT program. For the test group of welds, the process control rejection is valid.

b. Group 2, Weld #1

This weld showed considerable spitting, as may have been deduced from the relatively high infrared reading (Figure 13). The weld pulse voltage exceeded the high limits, and the dynamic setdown was below the minimum limit. The weld did, however, meet the criteria established for an acceptable weld relative to pull strength. The two or more weld waveform out-of-limit values satisfy the criterion established for showing the process control is unsatisfactory, such as would occur from operator error, or from faulty layout.

c. Group 4, Weld #3

This weld yielded a satisfactory pull strength; however, two or more rejections by individual NDT channels clearly indicated the simulated operator error. Further, the three weak welds fabricated in this group were detected by the instrumentation.

d. Group 6, Welds #1, #2, #3, #4 & #5

Each of these welds gave satisfactory pull strength results. Again, however, two or more rejections by individual NDT channels would, in a production situation, be indicative of a process control problem. In such cases, the welder would be shut down until the cause of the problem could be resolved. Therefore, the process control rejection is valid.

This particular test group was designed to simulate a situation whereby the ribbon had been routed on the wrong side of the component lead wire.

e. Group 10, Weld #1

Each of these welds gave satisfactory pull test results. This group was designed to simulate the condition of incorrect weld energy (40 watt-second instead of the 36 watt-second weld schedule); two or more NDT channel rejections again indicate lack of process control. This would detect misapplication by the operator of one weld schedule to a material pair requiring a different schedule.

f. Group 11, Welds #2 & #3

Each of these welds gave satisfactory pull strength results. This group was designed to simulate the condition of incorrect weld force (10 lbs. instead of 8 lbs. weld schedule); two or more NDT channel rejections again indicate lack of process control.

g. Group 12, Welds #3, #4 & #5

Each of these welds gave satisfactory pull strength results. This group was designed to simulate the condition of incorrect weld force (6 lbs. instead of 8 lbs. weld schedule); two or more NDT channel rejections again indicate lack of process control.

2. Experiment B-8

The background information pertinent to this specific experiment is tabulated below.

Material:	0.012" x 0.030" type A nickel ribbon
	0.017" Kovar, gold-plated
Average Breaking Pull Strength of Materials:	Nickel - 23.0 lbs Kovar - 19.4 lbs
Weld Schedule:	6 lbs, 11 watt-seconds
Pulse:	Long

Distribution of the measured weld parameters and pull strengths for the control group of welds at optimum weld schedule are illustrated in histographic form in Figures 14, 15, 16 and 17. The statistical information is shown in Table 5.

The NDT measurement results for the complete experiment are shown in Figure 18. The range of pull strength values and weld parameter measurements for the control group are represented by the solid black bars in the control group row of the chart.

Count - Similar Readings

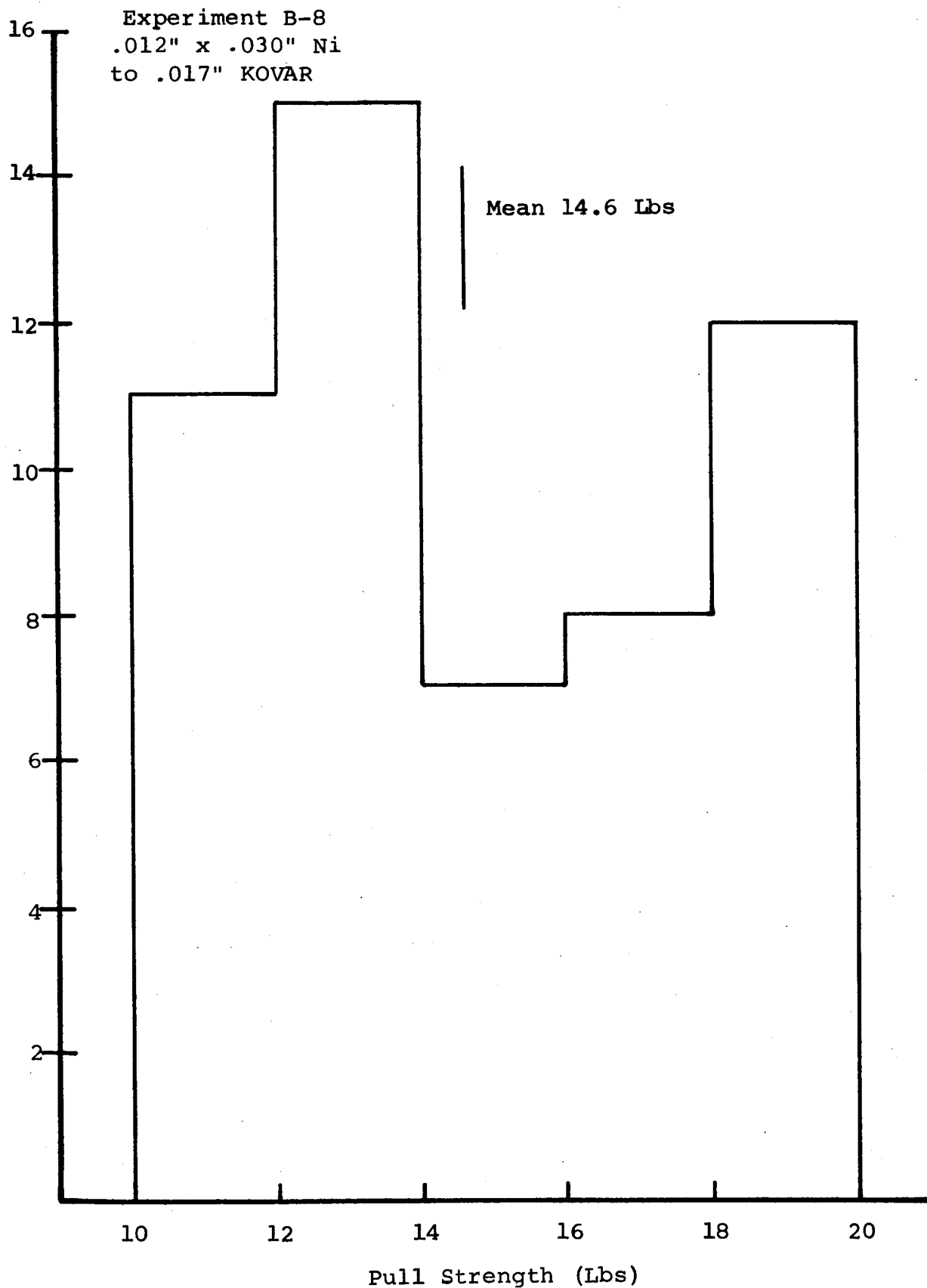


Figure 14
PULL STRENGTH DISTRIBUTION

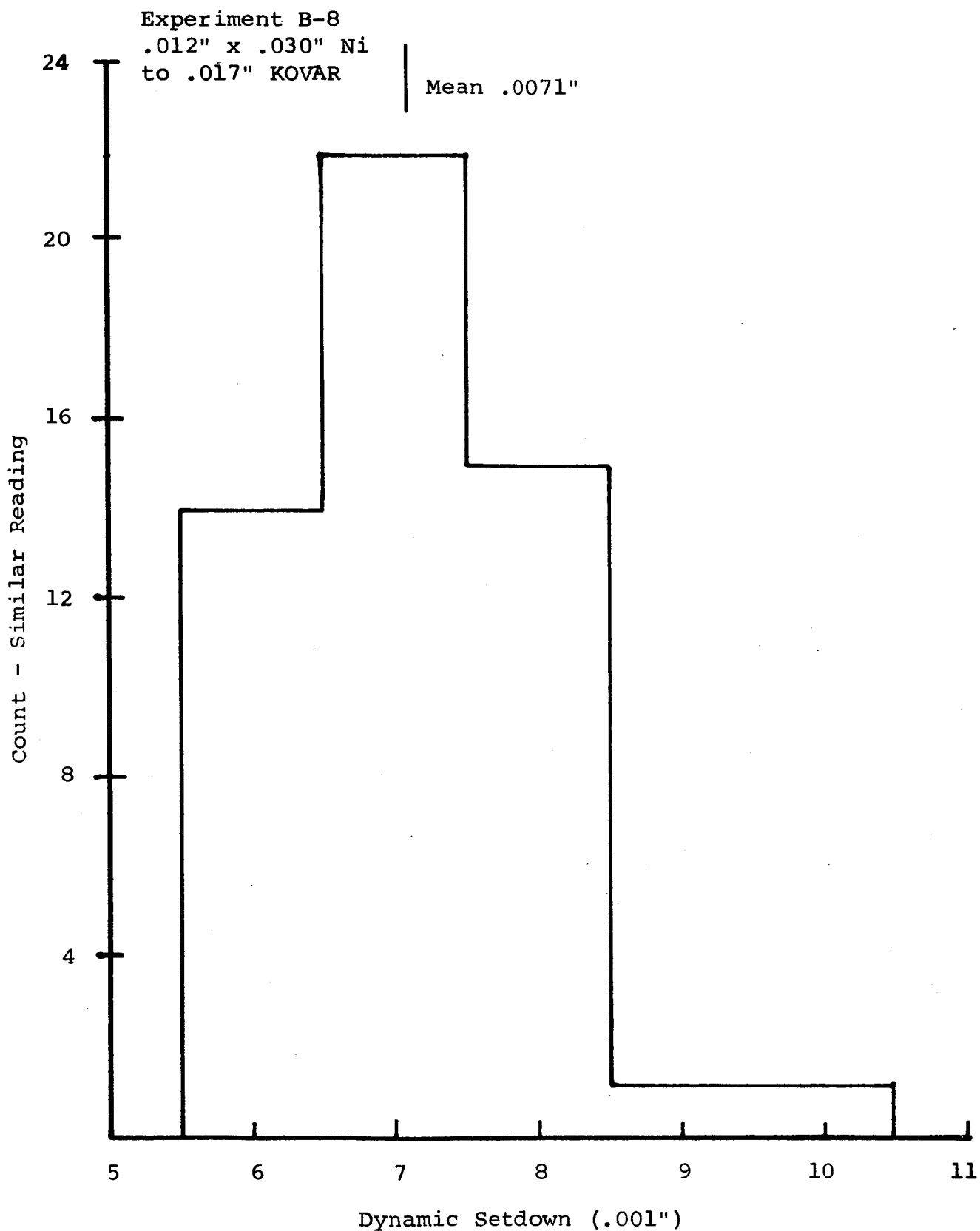


Figure 15

DYNAMIC SETDOWN DISTRIBUTION

Experiment B-8
.012" x .030" Ni
to .017" KOVAR

Mean 46.45 mV

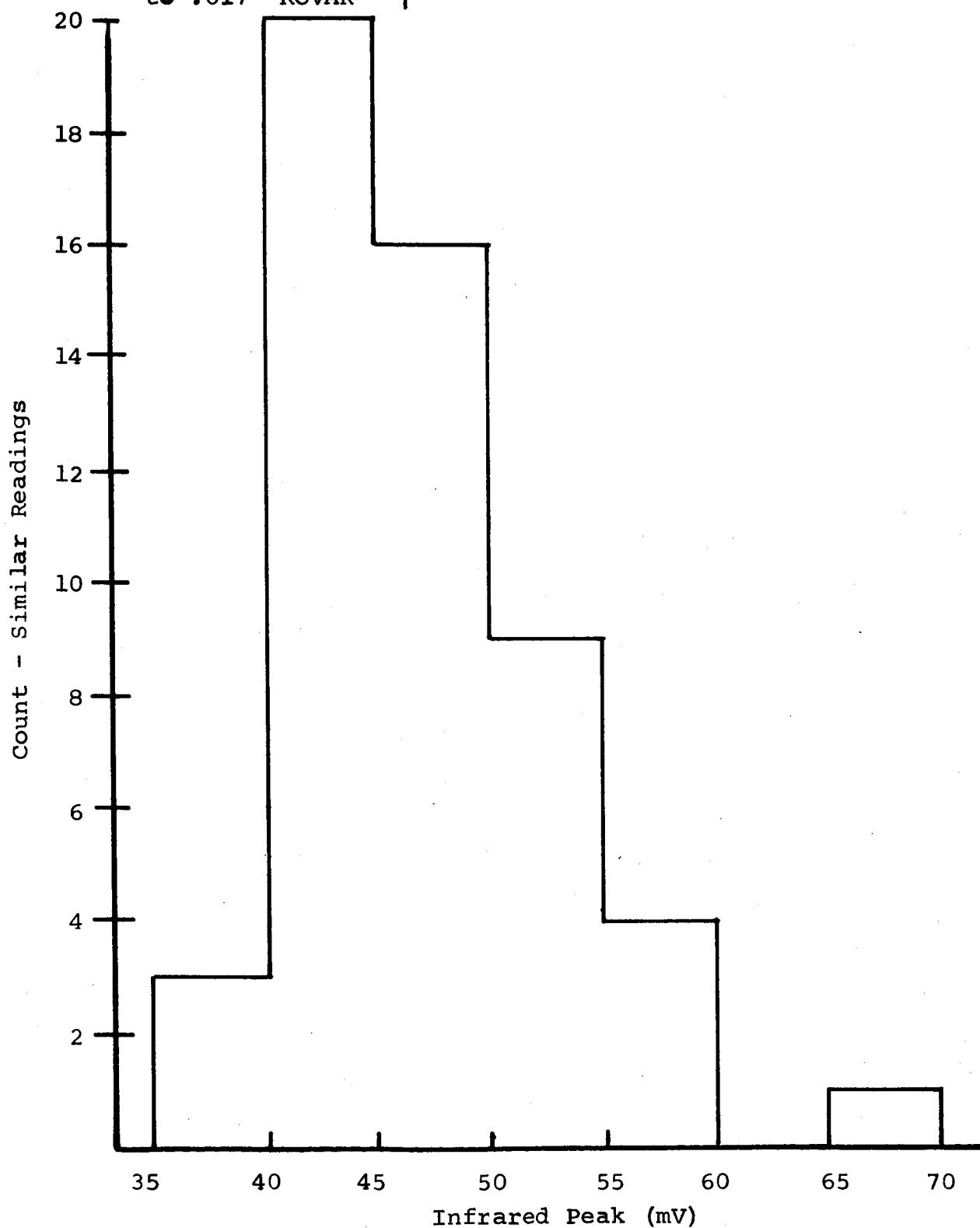


Figure 16

INFRARED PULSE AMPLITUDE DISTRIBUTION

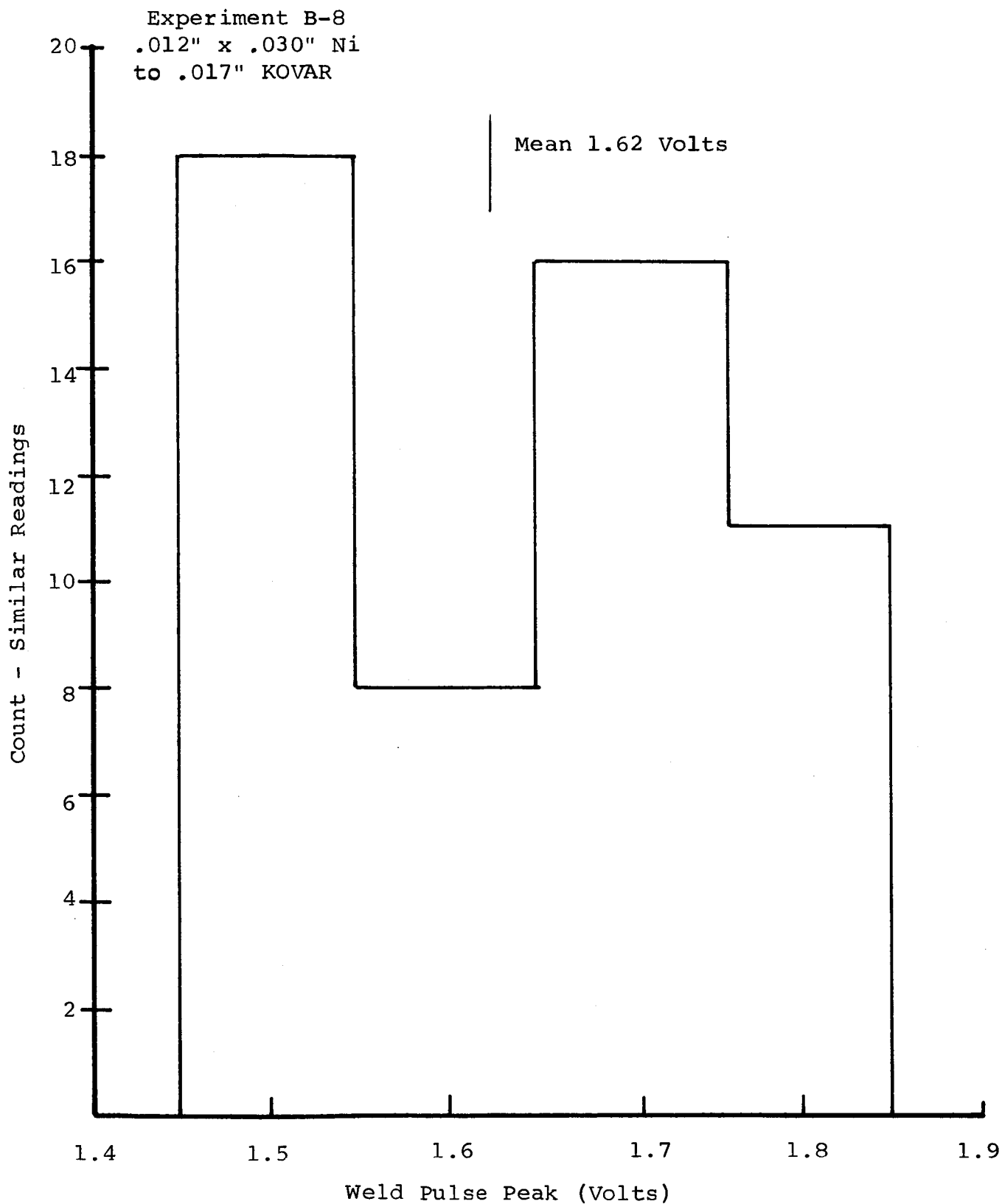


Figure 17

WELD VOLTAGE WAVEFORM - V/PEAK VALUE DISTRIBUTION

ATTRIBUTE	\bar{X}	σ	Range
Pull Strength (lbs)	14.6	2.7	8.6
Setdown (.001")	7.1	0.85	4.45
Infrared (mV) Cell Output	46.5	5.6	30
Weld Waveform Peak Value (mV)	1623	109	350

0.012" x 0.030" Nickel Ribbon
0.017" KOVAR, Gold Plated
Weld Schedule 6 lbs., 11 watt-seconds

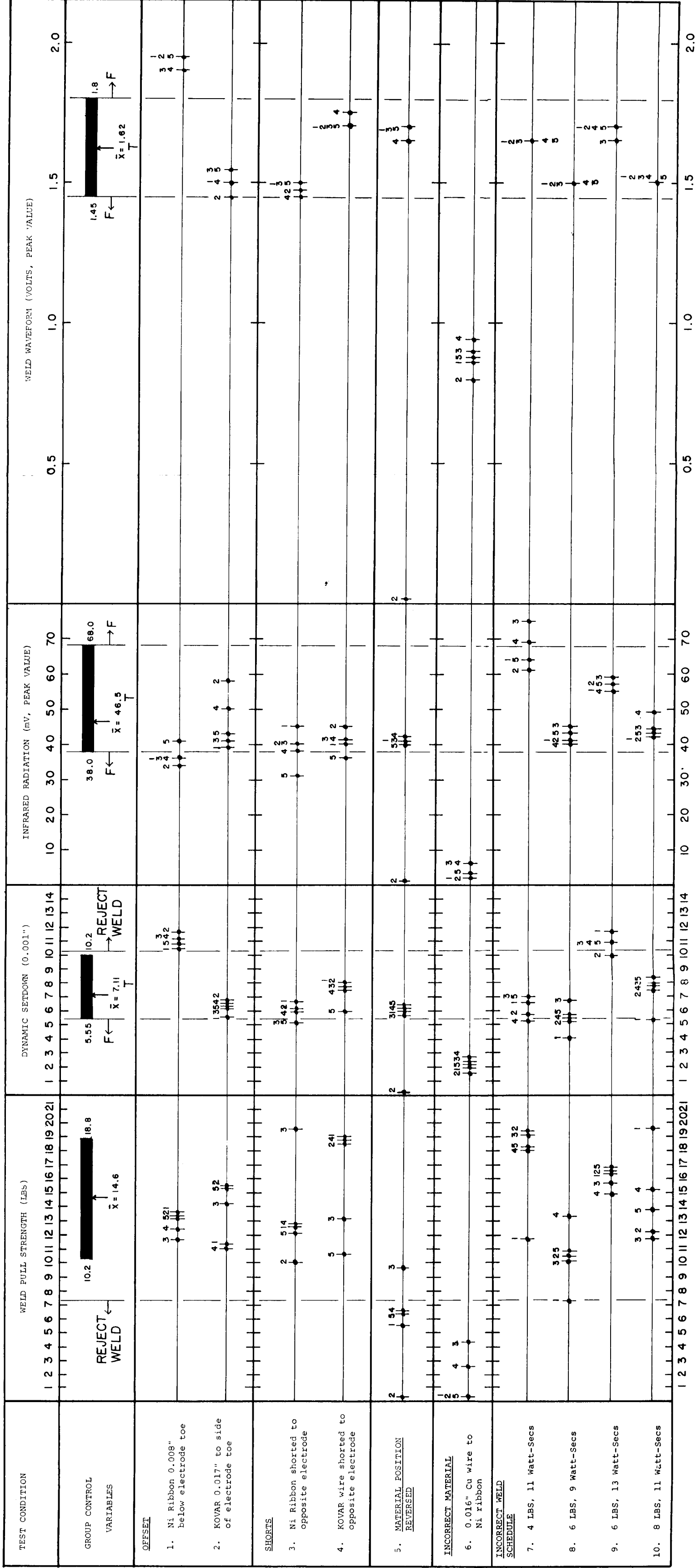
Table 5

CONTROL GROUP DATA SUMMARY

Experiment B-8

FIGURE 18

NDT RESULTS FOR 0.012" X 0.030" NICKEL RIBBON - 0.017" GOLD PLATED KOVAR WELDS (EXP. B-8)



FOLDOUT FRAME 1

FOLDOUT FRAME 2

FOLDOUT FRAME 3

The test configurations for the various welding condition groups are identified in the first column of the figures. Individual plotted parameter values are accompanied by an adjacent number that identifies the specific weld in each group of five.

The following are definitions used in this experiment for REJECT, FALSE and TRUE weld parameter signals.

Setdown:

REJECT - any dynamic setdown measurement greater than 10.2 mils. This signal, by itself, is an absolute cause for weld rejection.

FALSE - any setdown falling below the lower limit of the control group range (less than 5.55 mils).

TRUE - any setdown in the range from 5.55 mils to 10.2 mils.

Infrared Radiation:

FALSE - any signal above or below the control group range; i.e., less than 38.0 mV or greater than 68.0 mV.

TRUE - any signal within the control group range.

Weld Pulse:

FALSE - any signal above or below the control group range; i.e., less than 1.45 volts or greater than 1.8 volts.

TRUE - any signal within the control group range.

A Truth Table (Table 6) to identify the acceptable and defective welds was derived from the data presented in Figure 18.

The cases where measurement exceptions occurred are discussed below.

a. Group 3, Weld #5

Again, as in Experiment B-7, due to the experimental difficulty of reproducing the conditions of this shorted wire bad weld condition, it is possible that a bias may have been induced by bending the electrodes. This could have occurred in the process of malpositioning the material to create the desired shorted condition.

b. Group 5, Welds #1, #4 & #5

These welds were accepted by the NDT instrumentation and were below the minimum pull strength. The welds were bad since they exhibited pull strengths around 6 pounds. It should be noted that both the Setdown and Infrared readings (Figure 18) were markedly offset toward the lower acceptance limit and were closely clustered. The appearance of discrepancies with these characteristics would be readily flagged by NDT parameter process control range

Grp.	Variables	Weld No.	Setdown	Infra-red	Weld Wave-form	Individual Weld NDT Result	Weld Failure		NDT Test Valid	Process Control Monitor Valid
No.	Title					Accept Reject	Pull S. <7.3#	Setdn. >35%	YES NO	
1	Ni ribbon 0.008" below electrode toe	1	R	F	F	Reject		X	X	Yes
		2	R	F	F	Reject		X	X	
		3	R	F	F	Reject		X	X	
		4	R	F	F	Reject		X	X	
		5	R	T	F	Reject		X	X	
2	Kovar 0.017" to side of electrode	1	T	T	T	Accept			X	Materials Not Sensitive
		2	T	T	T	Accept			X	
		3	T	T	T	Accept			X	
		4	T	T	T	Accept			X	
		5	T	T	T	Accept			X	
3	Ni ribbon shorted to opposite electrode	1	T	T	T	Accept			X	Yes
		2	T	T	T	Accept			X	
		3	F	T	T	Accept			X	
		4	T	T	T	Accept			X	
		5	F	F	T	Reject	Weld/OK	weld/OK	X	
4	Kovar wire shorted to opposite electrode	1	T	T	T	Accept			X	Materials Not Sensitive
		2	T	T	T	Accept			X	
		3	T	T	T	Accept			X	
		4	T	T	T	Accept			X	
		5	T	F	T	Accept			X	

(Experiment B-8; 0.012" x 0.030" Ni, 0.017" gold-plated Kovar)

Sheet 1 of 3

Table 6
NDT MEASUREMENT TRUTH TABLE

Grp.	Variables		Weld No.	Setdown	Infra-red	Weld Wave-form	Individual Weld NDT Result	Weld Failure		NDT Test Valid		Process Control Monitor Valid	
	Title	Pull S. <7.3#						Setdn. >35%	YES	NO			
5	Material position reversed		1	T	T	T	Accept	X (5.5#)			X	No	
			2	F	F	F	Reject			X			
			3	T	T	T	Accept			X			
			4	T	T	T	Accept	X (6.5#)			X		
			5	T	T	T	Accept	X (6.3#)			X		
6	0.016" wire to Ni ribbon		1	F	F	F	Reject	X		X	Yes		
			2	F	F	F	Reject	X		X			
			3	F	F	F	Reject	X		X			
			4	F	F	F	Reject	X		X			
			5	F	F	F	Reject	X		X			
7	4 lbs. 11 watt seconds		1	T	T	T	Accept			X	Yes		
			2	T	T	T	Accept			X			
			3	T	T	F	Accept			X			
			4	F	F	F	Reject	Weld/OK	weld/OK			X	
			5	T	T	T	Accept			X			
8	6 lbs 9 watt seconds		1	F	T	T	Accept			X	Yes		
			2	F	T	T	Accept			X			
			3	T	T	T	Accept			X			
			4	T	T	T	Accept			X			
			5	T	T	T	Accept			X			

Grp. No.	Variables		Weld No.	Setdown	Infra- red	Weld Wave- form	Individual Weld NDT Result	Weld Failure		NDT Test Valid		Process Control Monitor Valid
	Title							Pull S. <7.3#	Setdn. >35%	YES	NO	
9	6 lbs 13 watt seconds		1	R	T	T	Reject		X	X	Yes	
			2	T	T	T	Accept		X			
			3	R	T	T	Reject	X	X			
			4	R	T	T	Reject	X	X			
			5	R	T	T	Reject	X	X			
10	8 lbs 11 watt seconds		1	T	T	T	Accept		X	Materials Not Sensitive		
			2	T	T	T	Accept	X				
			3	T	T	T	Accept	X				
			4	T	T	T	Accept	X				
			5	T	T	T	Accept	X				

plots (R) which would be maintained continually in production welding, as discussed in C, 1 of this section, last paragraph. This also indicates that the universal acceptance criteria established for the NDT feasibility evaluation may require adjustment for optimum effectivity. This will be considered during the NDT prototype evaluation program to be performed under actual production conditions.

c. Group 7, Weld #4

This weld was made at 4 pounds and 11 watt-seconds as compared to the 6 pounds and 11 watt-seconds weld schedule values. The pull strength was acceptable. As can be seen from the matrix chart, Figure 18, the Group 7 welds all tended to cluster toward the low end of the setdown limits, and toward the high end of the infrared limits. This indicates the NDT measurements to be responsive in trend to the lighter welding electrode force. Weld firing at low welder-force is very unlikely, unless there has occurred some consistent shift in the machine operation. This trending would appear to provide a valid indication of change in process parameters, which will be explored later during production evaluation.

3. Experiment B-9

The background information pertinent to this specific experiment is tabulated below:

Material:	0.012" x 0.030" type A nickel ribbon
	0.020" Dumet, gold-plated

Average Breaking
Pull Strength of
Materials:

Nickel - 23.0 lbs
Dumet - 21.6 lbs

Weld Schedule:

8 lbs, 16 watt-seconds

Pulse:

Long

Distribution of the measured weld parameters and pull strengths for the control group of welds at optimum weld schedule are illustrated in histographic form in Figures 19, 20, 21 and 22. The statistical information is shown in Table 7.

The NDT measurement results for the complete experiment are shown in Figure 23. The range of pull strength values and weld parameter measurements for the control group are represented by the solid black bars in the control group row of the chart.

The test configurations for the various welding condition groups are identified in the first column of the figure. Individual plotted parameter values are accompanied by an adjacent number that identifies the specific weld in each group of five.

The following are definitions used in this experiment for REJECT, FALSE and TRUE weld parameter signals.

Setdown:

REJECT - any dynamic setdown measurement greater than 11.2 mils. This signal, by itself, is an absolute cause for weld rejection.

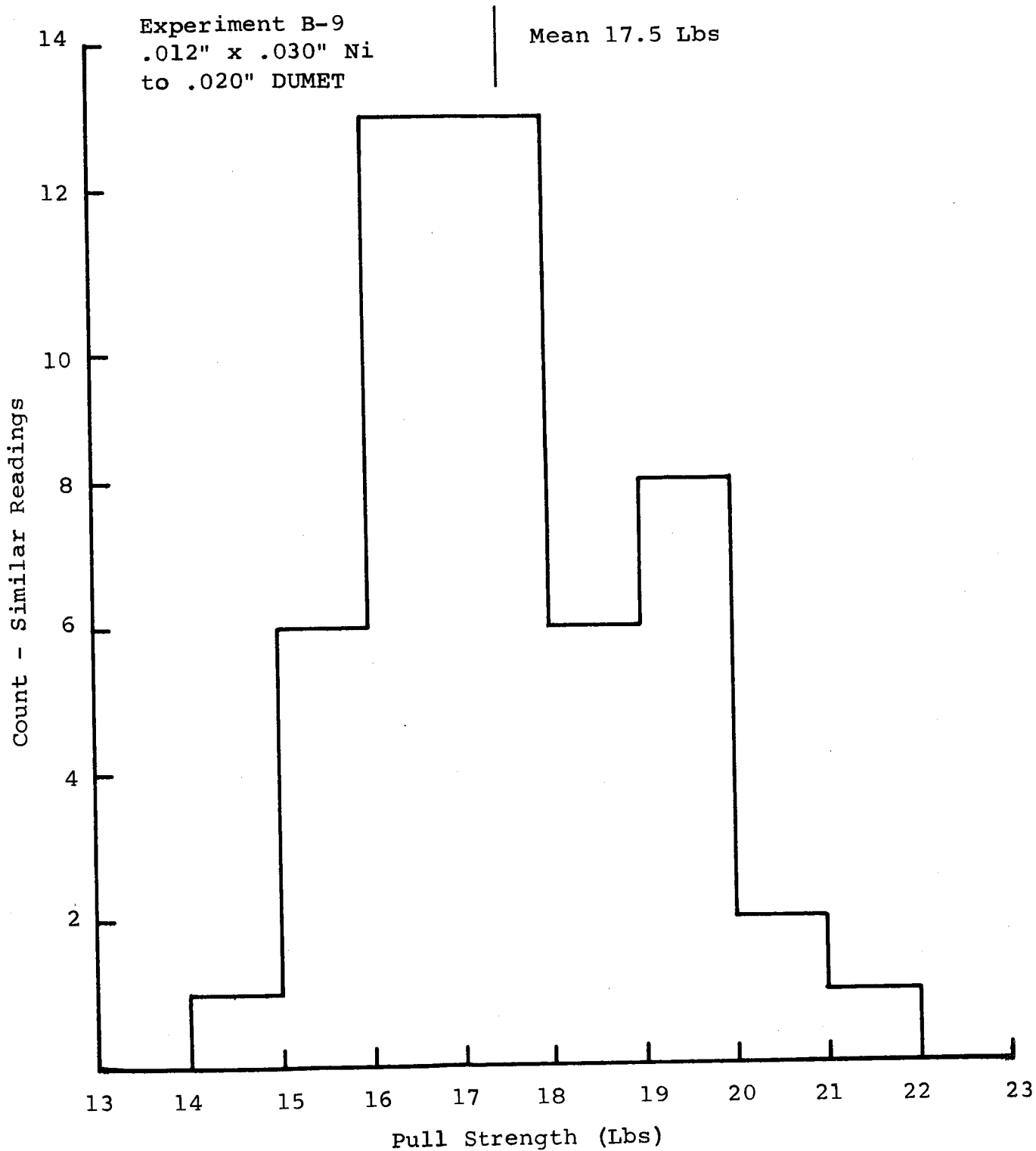


Figure 19
PULL STRENGTH DISTRIBUTION

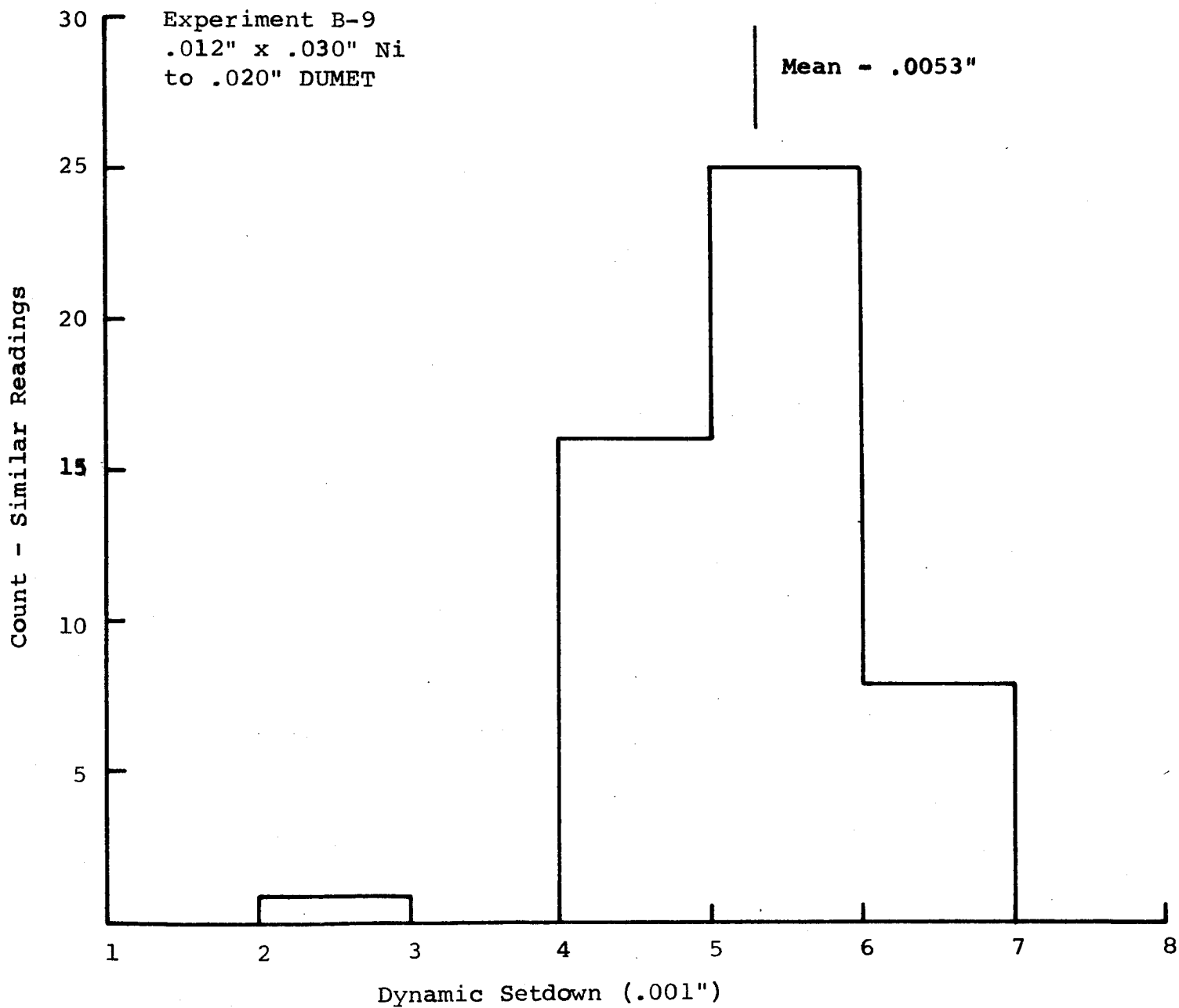


Figure 20
DYNAMIC SETDOWN DISTRIBUTION

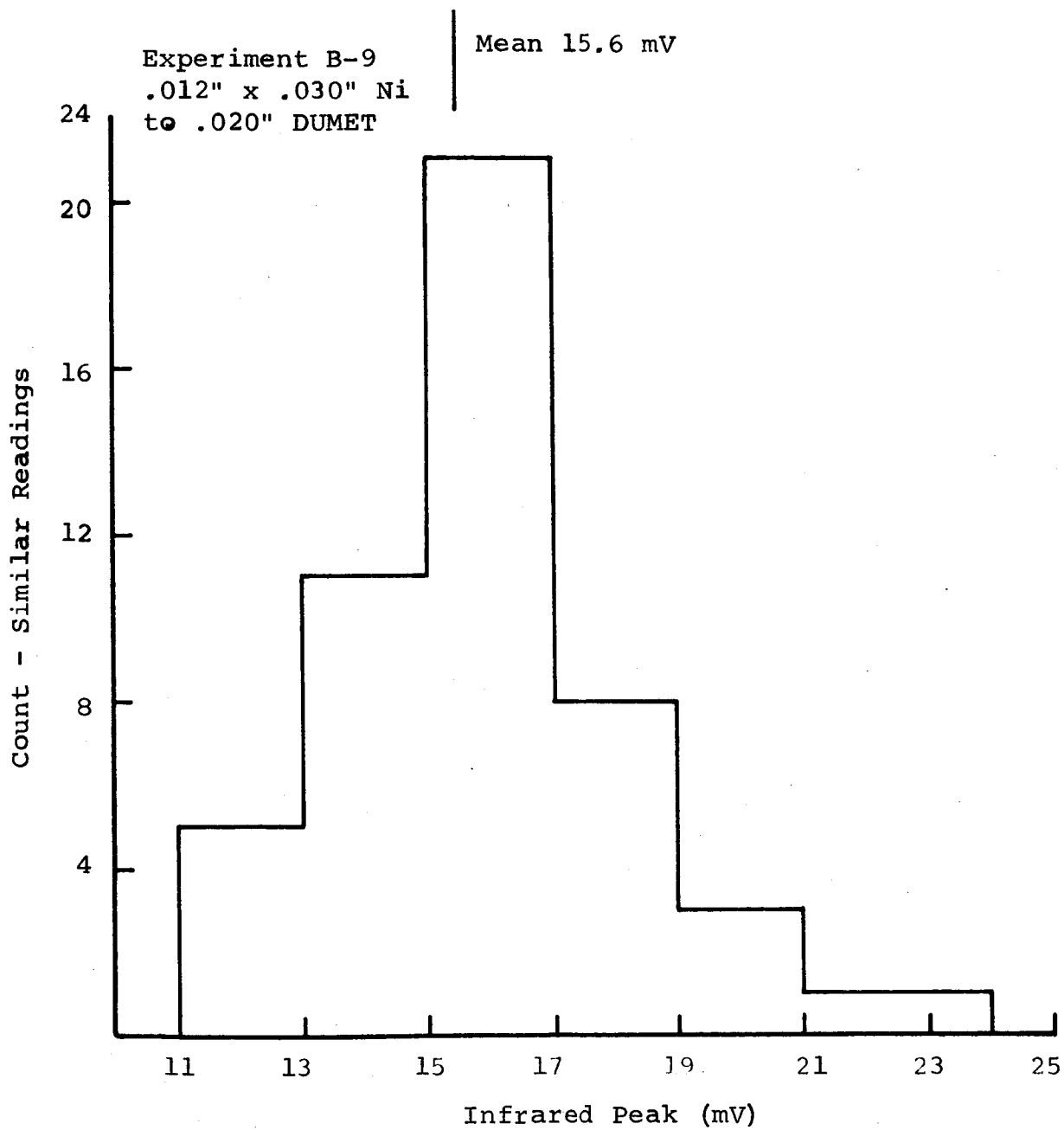


Figure 21
INFRARED PULSE AMPLITUDE DISTRIBUTION

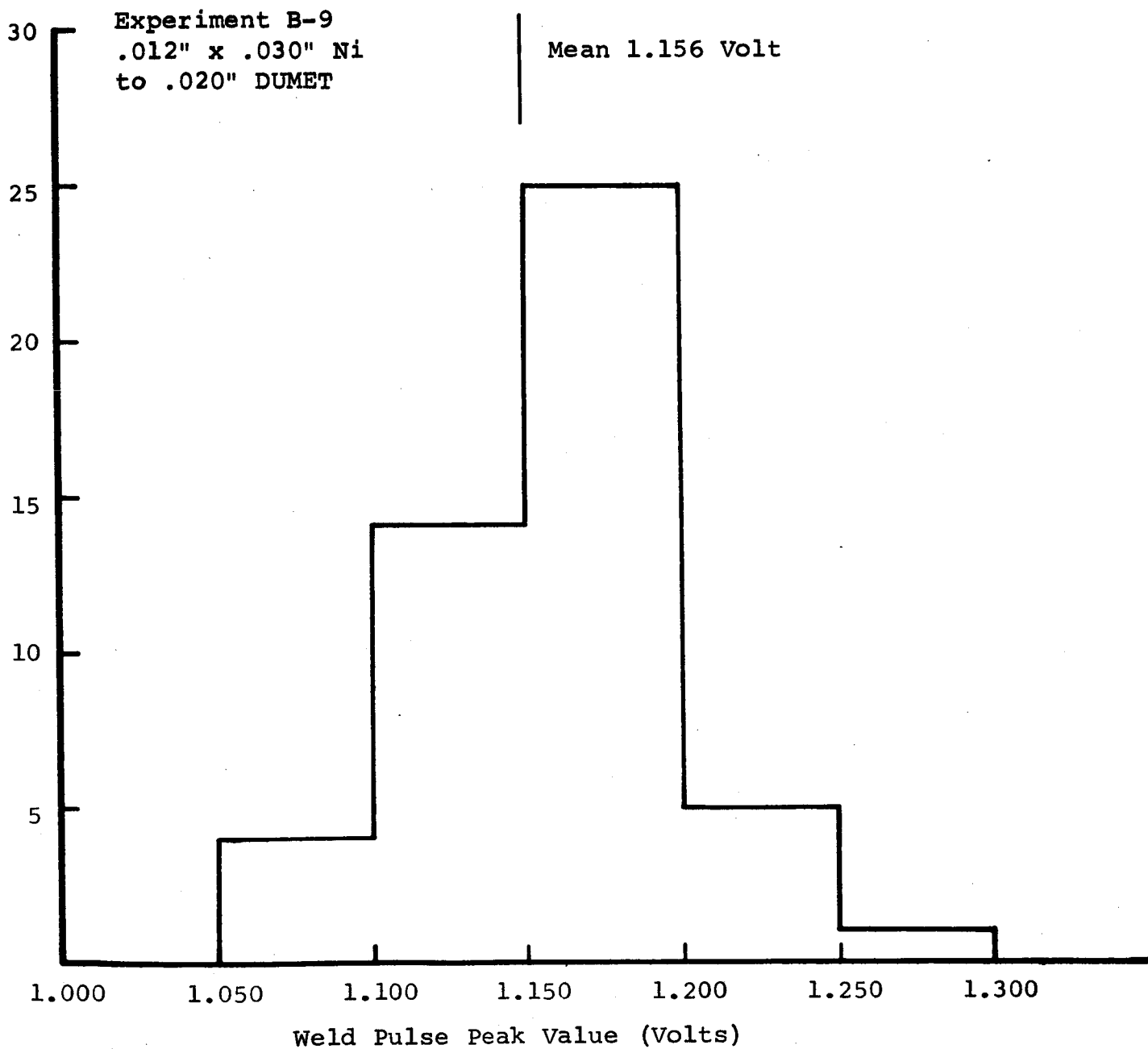


Figure 22

WELD VOLTAGE WAVEFORM - V/PEAK VALUE DISTRIBUTION

ATTRIBUTE	\bar{X}	σ	Range
Pull Strength (lbs)	17.5	1.53	6.9
Setdown (.001")	5.3	0.69	3.84
Infrared (mV) Cell Output	15.6	2.45	13.0
Weld Waveform Peak Value (mV)	1160	37.6	180

0.012" x 0.030" Nickel Ribbon

0.020" DUMET, Gold Plated

Weld Schedule 8 lbs., 16 watt-seconds

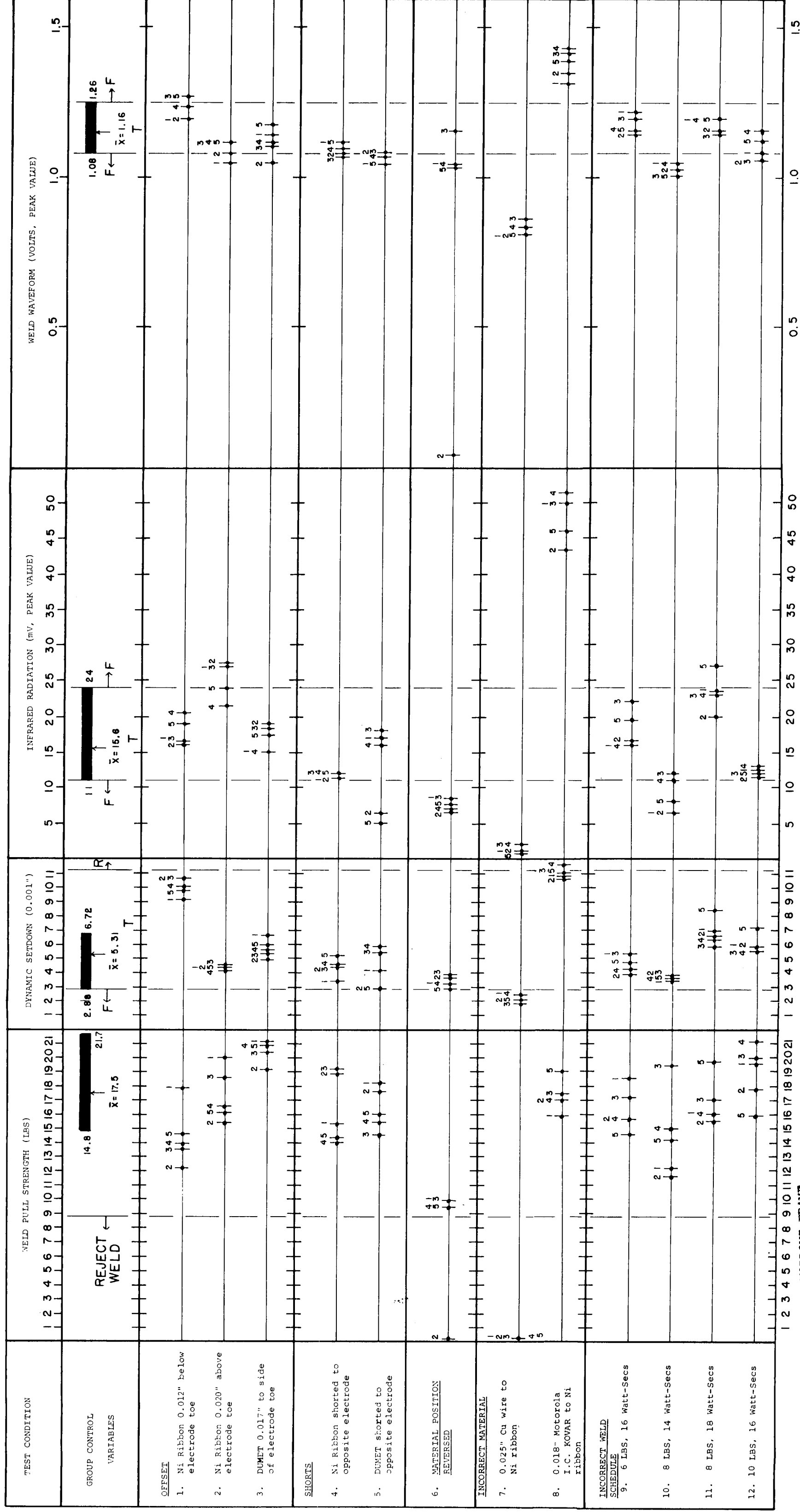
Table 7

CONTROL GROUP DATA SUMMARY

Experiment B-9

FIGURE 23

NDT RESULTS FOR 0.012" X 0.030" NICKEL RIBBON - 0.020" DUMET (EXP. B-9)



FALSE - any setdown falling below the lower limits of the control group range (less than 2.88 mils).

TRUE - any setdown in the range from 2.88 mils to 11.2 mils.

Infrared Radiation:

FALSE - any signal above or below the control group range; i.e., less than 11.0 mV or greater than 24.0 mV.

TRUE - any signal within the control group range.

Weld Pulse:

REJECT |R| - any signal with power supply pulse polarity control in wrong position (gives NDT pulse of reversed polarity).

FALSE - any signal above or below the control group range; i.e., less than 1.08 volts or greater than 1.26 volts.

TRUE - any signal within the control group range.

A Truth Table (Table 8) to identify the acceptable and defective welds was derived from the data presented in the matrix.

The cases where measurement exceptions occurred are discussed below.

Grp. No.	Variables		Weld No.	Setdown	Infra- red	Weld Wave- form	Individual Weld NDT Result	Weld Failure		NDT Test Valid		Process Control Monitor Valid
	Title	Accept Reject						Pull S. <8.7#	Setdn. >35%	YES	NO	
1	Ni ribbon 0.012" below electrode toe		1	T	T	T	Accept				X	Yes
			2	T	T	T	Accept				X	
			3	T	T	T	Accept				X	
			4	T	T	T	Accept				X	
			5	T	T	F	Accept				X	
2	Ni ribbon 0.020" above electrode toe		1	T	F	T	Accept				X	Yes
			2	T	F	T	Accept				X	
			3	T	F	T	Accept				X	
			4	T	T	T	Accept				X	
			5	T	T	T	Accept				X	
3	Dumet 0.017" to side of electrode		1	T	T	T	Accept				X	Materials Not Sensitive
			2	T	T	F	Accept				X	
			3	T	T	T	Accept				X	
			4	T	T	T	Accept				X	
			5	T	T	T	Accept				X	
4	Ni ribbon shorted to opposite electrode		1	T	T	T	Accept				X	Materials Not Sensitive
			2	T	T	T	Accept				X	
			3	T	T	F	Accept				X	
			4	T	T	T	Accept				X	
			5	T	T	T	Accept				X	

(Experiment B-9; 0.012" x 0.030" Ni, 0.020" gold-plated Dumet)

Sheet 1 of 3

Table 8
NDT MEASUREMENT TRUTH TABLE

Grp. No.	Variables		Weld No.	Setdown	Infra- red	Weld Wave- form	Individual Weld NDT Result	Weld Failure		NDT Test Valid		Process Control Monitor Valid
	Title	Accept Reject						Pull S. <8.7#	Setdn. >35%	YES	NO	
5	Dumet shorted to opposite electrode		1	T	T	F	Accept				X	Yes
			2	T	F	T	Accept				X	
			3	T	T	T	Accept				X	
			4	T	T	F	Accept				X	
			5	T	F	F	Reject	Weld/ OK	Weld/ OK		X	
6	Material position reversed		1	T	F	F	Reject	Weld/ OK	Weld/ OK		X	Yes
			2	T	F	F	Reject	X		X		
			3	T	F	T	Accept			X		
			4	T	F	F	Reject	Weld/ OK	Weld/ OK		X	
			5	T	F	F	Reject	Weld/ OK	Weld/ OK		X	
7	0.025" Cu wire to Ni ribbon		1	F	F	F	Reject	X		X	Yes	
			2	F	F	F	Reject	X		X		
			3	F	F	F	Reject	X		X		
			4	F	F	F	Reject	X		X		
			5	F	F	F	Reject	X		X		
8	0.018" Motorola I.C. Kovar to Ni ribbon		1	T	F	F	Reject	Weld/ OK	Weld/ OK		X	Yes
			2	T	F	F	Reject	Weld/ OK	Weld/ OK		X	
			3	T	F	F	Reject	Weld/ OK			X	
			4	R	F	F	Reject		X	X		
			5	T	F	F	Reject	Weld/ OK			X	

Table 8

Grp. No.	Variables		Weld No.	Setdown	Infra- red	Weld Wave- form	Individual Weld NDT Result	Weld Failure		NDT Test Valid		Process Control Monitor Valid
	Title							Pull S. <8.7#	Setdn. >35%	YES	NO	
9	6 lbs 16 watt seconds		1	T	T	T	Accept			X		Materials Not Sensitive
			2	T	T	T	Accept			X		
			3	T	T	T	Accept			X		
			4	T	T	T	Accept			X		
			5	T	T	T	Accept			X		
10	8 lbs 14 watt seconds		1	T	F	F	Reject	Weld/OK	Weld/OK		X	Yes
			2	T	F	F	Reject	Weld/OK	Weld/OK		X	
			3	T	T	F	Accept			X		
			4	T	T	F	Accept			X		
			5	T	F	F	Reject	Weld/OK	Weld/OK		X	
11	8 lbs 18 watt seconds		1	T	T	T	Accept			X		Materials Not Sensitive
			2	T	T	T	Accept			X		
			3	T	T	T	Accept			X		
			4	T	T	T	Accept			X		
			5	T	F	T	Accept			X		
12	10 lbs 16 watt seconds		1	T	T	T	Accept			X		Yes
			2	T	T	F	Accept			X		
			3	T	T	F	Accept			X		
			4	T	T	T	Accept			X		
			5	T	T	T	Accept			X		

Table 8

a. Group 5, Weld #5

The pull test results were satisfactory for this weld. As in B-7 and B-8, due to the experimental difficulty of reproducing the conditions of this shorted wire bad weld condition, it is possible that a bias may have been induced by bending the electrodes. This could have occurred in the process of malpositioning the material to create the desired shorted condition.

b. Group 6, Welds #1, #4 & #5

These welds were made with reversed material position, and were adequate in pull strength, but failed the NDT test. All of the infrared NDT measurements were out of limit and four of the weld waveform NDT measurements were out of limit, thus clearly flagging a process control problem.

c. Group 8, Welds #1, #2, #3 & #5

All five of the infrared and all five of the weld waveform NDT measurements were out of limits, thus flagging a process control problem, even though the weld strengths were acceptable. The dynamic setdown NDT measurements all clustered close to the maximum limit allowed, as may be observed from the matrix chart.

d. Group 10, Welds #1, #2 & #5

These welds were made at an energy level 2 watt-seconds under the 8 pound, 16 watt-second weld schedule values. While the pull strengths are satisfactory, again all five

of the voltage waveform NDT values were below the minimum limit, and all of the infrared values clustered at the low end. Both of these are indicative of reduced welder energy.

APPENDIX

APPENDIX A

REFERENCES*

1. Calibration of Miniature Resistance Welding Equipment. J. L. Cox. Proceedings of National Electronic Packaging and Production Conference, New York, N.Y., 21-23 June 1966.
2. Fracture. H. T. Corten and F. R. Park. International Science and Technology, 15: 24-36 March 1963.
3. Weldment Flexure Testing. Successor to Metallurgical Analysis. J. R. Saul. SAE-Electronic Packing Conference, 27-28 October 1964.
4. Nondestructive Testing: Trends and Techniques. NASA SP-5082, 1967.
5. Electronic Methods for Nondestructive Testing of Nonferrous Wire. Wire and Wire Products, 40: 1294-97, Sept. 1965.
6. 3D Welded Module Design and Manufacturing Control Parameters. H. F. Sawyer. Ninth Symposium Welded Electronics Packing Association, 26-27 February 1964.
7. Status of Investigation of Nondestructive Testing for Wire-Welding. W. V. Sterling, Inc., to C. M. Adamowicz, LMSC, 16 March 1962.
8. A Practical Approach to Reliability in Welded Circuits. J. M. Eckhart, R. F. Lyon. Fifth Symposium of Electronic Component Welding Association, 21 August 1961.
9. Dynamic Resistance Test of Spot Welds. L. B. Cherry. IEEE Transactions, Communications and Electronics, pp. 121-123, May 1963.

*Over 120 references were actually examined. Those considered most relevant to the NDT program are listed here.

10. Evaluation of the Resistance Microwelding Process by Infrared Energy Measurement. S. Leonard and J. K. Lee. Transactions of the Infrared Sessions at the Spring Convention of the Society for Nondestructive Testing, 22-26 February 1965.
11. Infrared Exposes Hidden Circuit Flaws. Riccardo Vanzetti. Electronics, 40: 100-104, 3 April 1967.
12. Infrared Fiber Optics and Infrared Nondestructive Testing. R. J. Simms. Transactions of the Infrared Sessions at the Spring Convention of the SNT, 22-26 February 1965.
13. The APL Resistance Welder. R. C. Evans and A. Dargis. Technical Memorandum TG-687, The Johns Hopkins University, Applied Physics Laboratory, May 1965.
14. A Nondestructive Test Method for Process Control of Cross-Wire Resistance Welds. R. F. Peluso. Eighth Welded Electronic Packaging Association Symposium, Syracuse, N.Y. June 1963.
15. Investigation of Nondestructive Testing Techniques for Wire Welding, Report No. 2 to LMSC. W. V. Sterling, Inc. November 1962.
16. Nondestructive Inspection Device for Welded Connections. W. C. Croucher. Sixth International Electronic Circuit Packaging Symposium, concurrent with WESCON, San Francisco. August 23-24, 1965.
17. A New Method for the Nondestructive Testing of Spot Welds. Gunter Wilkens, Institute for Construction Materials at the Technical University, Hannover, Germany. Translation RSIC-TT-64-71436 (AD 606 048).
18. Ultrasonic In-Process Inspection of Resistance Spot Welds. G. E. Burbank and W. D. Taylor (Frankford Arsenal). Welding Journal, 44: -193s-198s, May 1965.
19. In-Process Welding Control Provided by Ultrasonics. Author not given (cites work by the Boeing Co.), Iron Age, 198:134, November 17, 1966.
20. Ultrasonic View of a Spot Weld. Author not given. Welding Engineer, 51: 44-45, November 1966.

APPENDIX B

LIST OF ORGANIZATIONS AND PERSONS CONTACTED

1. General Dynamics, Pomona. Robert Lennon, Al M. Murphy, H. F. Sawyer.
2. Aerojet General Corporation, Azusa. Arthur H. Lawrence, Jerry G. Hoover, Joe Slaughter.
3. Weldmatic Division, Unitek Corporation, Monrovia. Ernest F. Koshinz.
4. Electro-Optical Systems, Inc., Pasadena. Richard J. La Belle, Robert La Rock, Paul Williams.
5. Analog Technology Corporation, Pasadena. Dr. J. H. Marshall, Julium Jodele, T. M. Harrington.
6. Marshall Laboratories, Torrance. Don Kratzer, Roy Currence.
7. TRW Systems, Redondo Beach. John R. Sosoka, Robert Norris.
8. Jet Propulsion Laboratory, Pasadena. Robert G. Stokeley; Ray M. Jorgensen, Del C. Maxfield, and Larry Conway.
9. WEMS, Inc., Hawthorne. Robert Hood, Ben H. Cogan, John Strasshofer.
10. Martin-Marietta Corporation, Denver, Colorado. Ray F. Peluso, W. C. Croucher.
11. U. S. Naval Avionics Facility, Indianapolis, Indiana. D. L. Cheak, C. R. Reuter, R. J. Smith, R. E. Bryan, A. T. Updike.
12. Wright-Patterson Air Force Base, Dayton, Ohio. Paul Poliquin, R. M. Long.
13. Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio. Dr. R. E. Deith, J. L. Easterday, Cliff Seal, Al Leatherman.

21. Mechanical Properties of Films, the Dynamic Testing of Micro Samples. R. S. Jackson & W. Simpson, Journal of Applied Chemistry, 15: 230-232. May 1965.
22. Parallel Gap Welding to Copper Printed Circuit Boards. A. Koudounaris. Report SM-49158, July 1966, Missile and Space Systems Division, Douglas Aircraft Company, Santa Monica, California.
23. Development of Weld Schedules and Process Control. J. R. Gates. Published by Weldmatic Division, Unitek.
24. Application of the Ultrasonic Resonance Technique to Inspection of Miniature Soldered and Welded Connections. R. G. Bayer and T. S. Burke. Materials Evaluation, pages 20-24. January 1967.
25. Welding for Electronic Assemblies. NASA SP-5011. Technology Handbook, National Aeronautics and Space Administration, November 1964.

14. Goddard Space Flight Center, Greenbelt, Md. Russell E. Dorrell, Abe Pilch.
15. NASA Headquarters, Washington, D. C. Dr. J. E. Condon, J. R. Miles.
16. AEC, Germantown, Md. Ken Horton, James Mershon, AEC; Sam Snyder, NASA.
17. Applied Physics Laboratory, Johns Hopkins University, Silver Spring, Md. R. W. Cole, Dr. R. C. Evans.
18. Bendix-Pacific Division, Sylmar, California. Ralph Lamm, George Williams, Karl Stevenson.
19. EPI/Vostron, Anaheim, California. J. R. Gates.
20. Northrop Nortronics, Anaheim, California. Lee Mueller, Lloyd Scherbinske.
21. Hughes Vacuum Tube Division, Oceanside, California. C. A. Rollins, D. Blough, William Hill.
22. Lockheed Missiles and Space Company, Sunnyvale, California. Dr. Hans M. Wagner, Dale R. Torgeson, Ben F. Juscen, Fletcher R. Sullivan, Dale Adams.
- *23. The Sippican Corporation, Marion, Massachusetts. R. M. Steigerwald, Winthrop Baylies.
- *24. Kulicke and Soffa Industries, Ft. Washington, Pa. Ed Haigler.
- *25. U. S. Naval Air Development Center, Johnsville, Pa. E. R. Mullen.
- *26. Massachusetts Institute of Technology, Cambridge, Mass. Eldon Hall, Ed Duggan.

*Contacts made by telephone.